Guest Lecture: Circumbinary Exoplanets

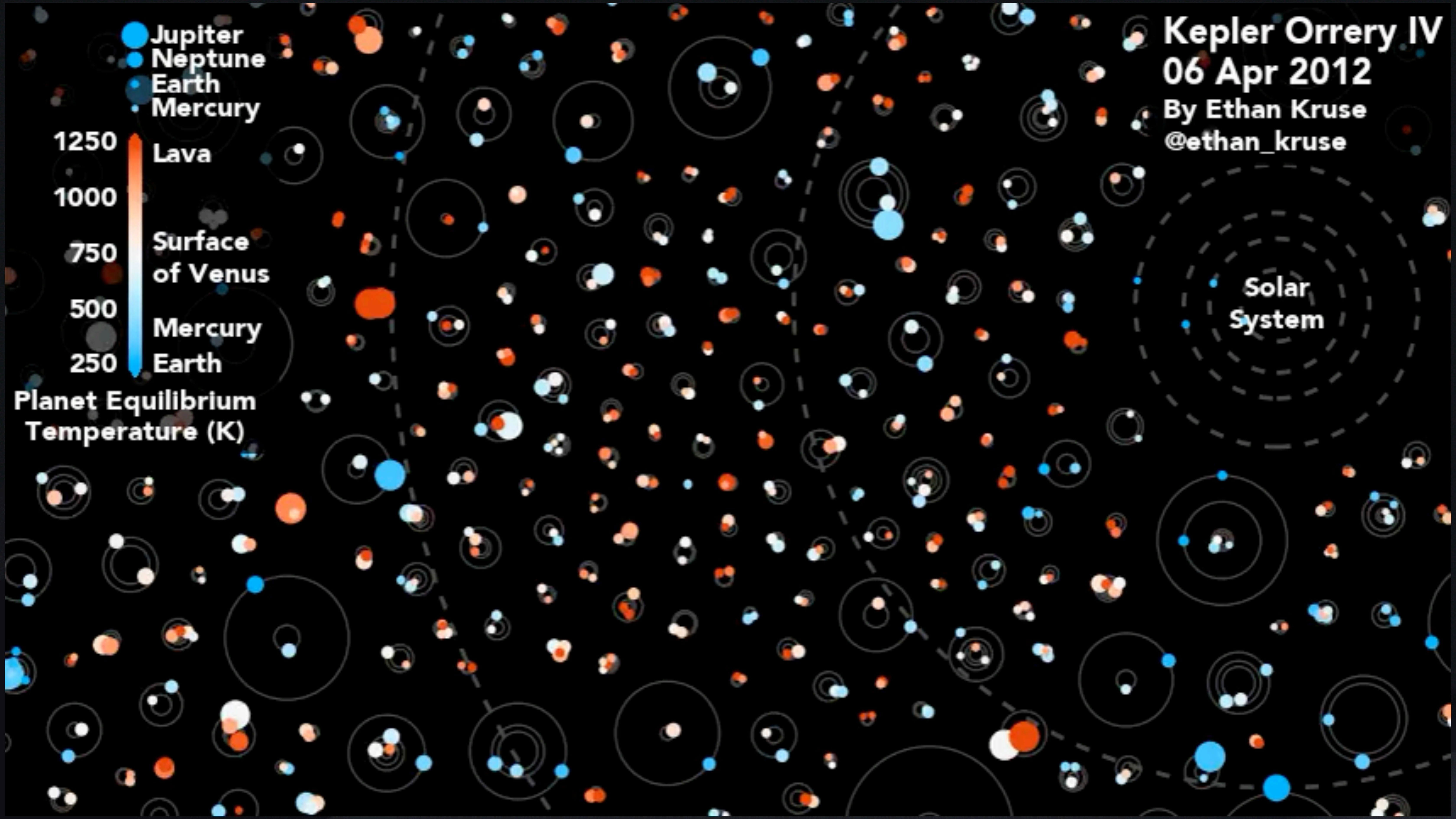
PHYS 480/581: Planetary Astrophysics

Presented by Dominic Oddo

On Wednesday, November 13th, 2024

Exoplanets

- ✳ Exoplanet - any planet orbiting a star that isn't our sun
- ✳ planetary systems are common in the universe and incredibly diverse in size, composition, and orbital behavior
- ✳ "hot-Jupiters", "super-Earths", and "water worlds"



All of the Kepler multi-planet systems
1815 planets in 726 systems, same size scale of the solar system

Transits

How it works:

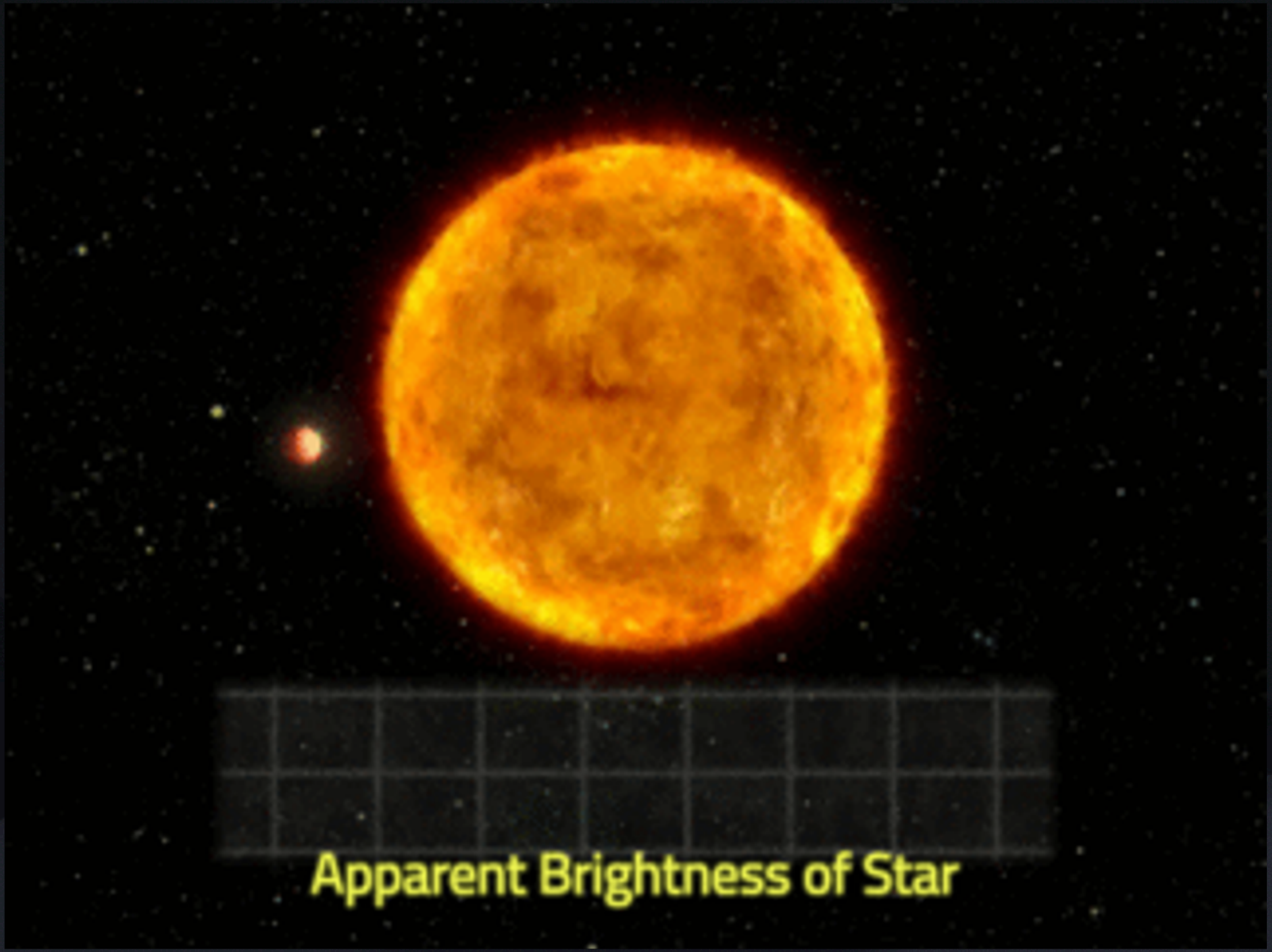
- Monitor the brightness of a star over time, searching for consistent, regular drops in brightness, indicating a planet passing by!

Pros:
- Easy to monitor many stars
- Constrains size of planet

Cons:
- Biased towards large, close planets
- Planets need to be aligned

Interesting fact:

- Most discoveries with this method!

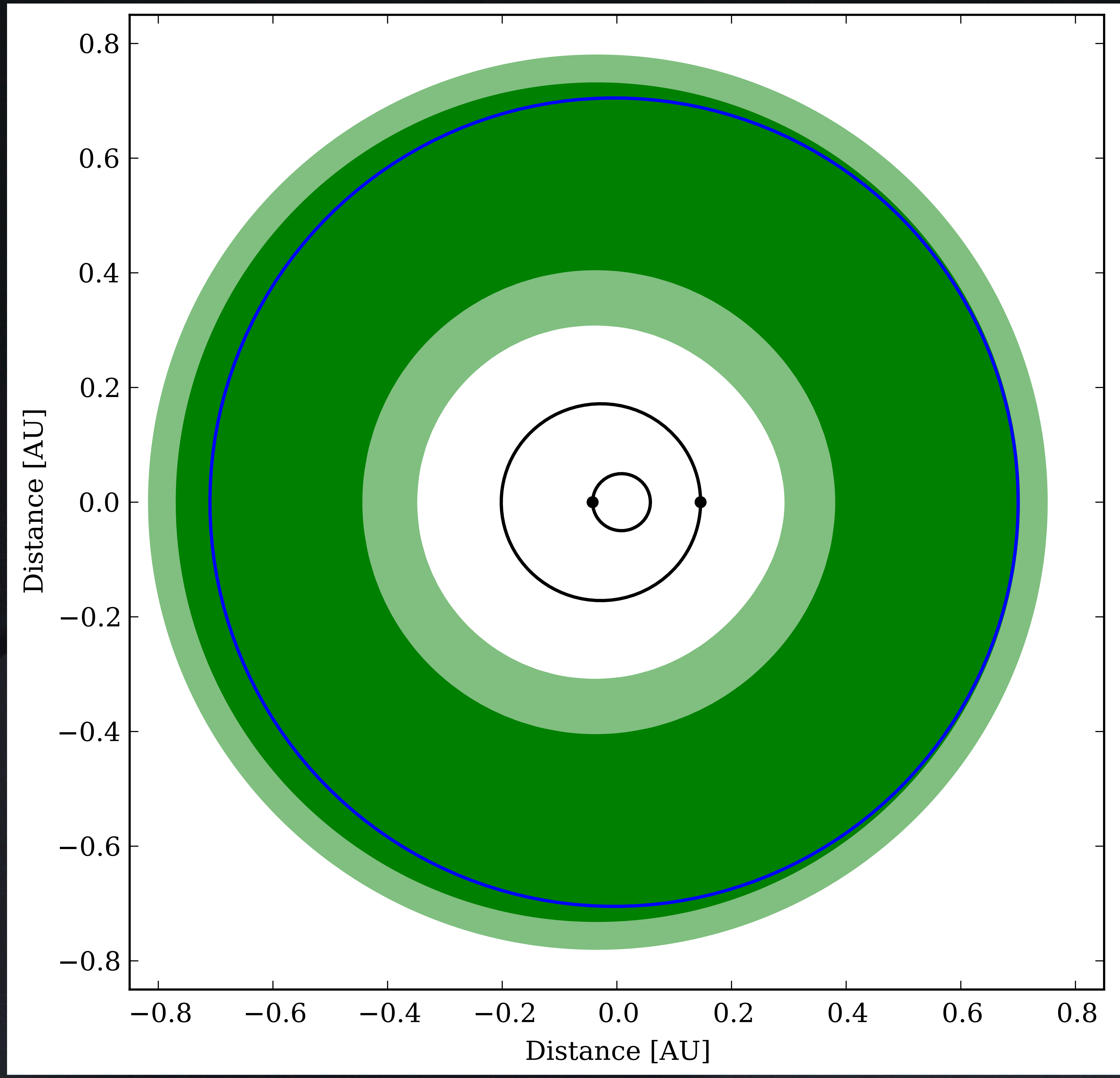


Courtesy: NASA

Circumbinary Exoplanets

An introductory understanding

- ✳ Orbit outside both stars in a tight binary (periods of order days)
- ✳ An interesting backdrop to study both binary star AND planet formation
- ✳ Thinking beyond single stars
  - ✳ More stars have buddies than not
- ✳ A strikingly small number discovered so far, but so much community interest



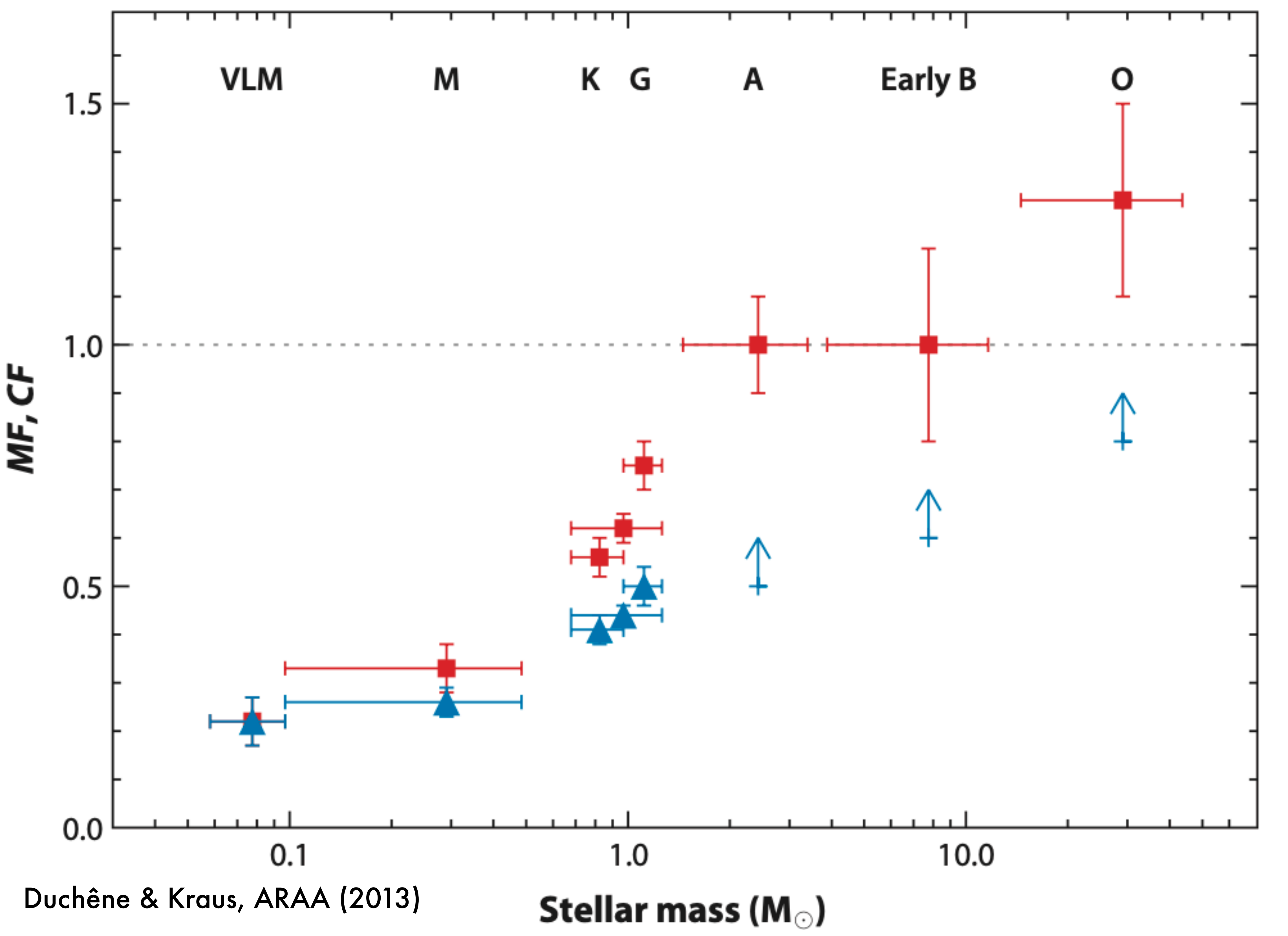
Overview

- ✳ Binaries & eclipsing binaries
  - ✳ Introduction and importance
- ✳ Formation of tight binary stars
- ✳ Circumbinary planets (CBPs)
  - ✳ Formation and other science
  - ✳ The population of known CBPs
  - ✳ How do we find them?

Credit: Astronomical Society of Edinburgh

Stellar Multiplicity

Binaries are quite common!



Duchêne & Kraus, ARAA (2013)

- ✳ Although a slight majority of sun-like stars are single, there are more stars in our galaxy in binary or higher order systems than in single systems!
- ✳ MF (multiplicity frequency, blue): fraction of multiple systems
- ✳ CF (companion frequency, red): average number of companions per target
- ✳ MF and CF change with stellar mass

Picture a binary...

<u>Are you Sirius...</u>

RA: $06^h\ 45^m\ 08.917^s$

Dec: −16° 42′ 58.02″

V mag = -1.46

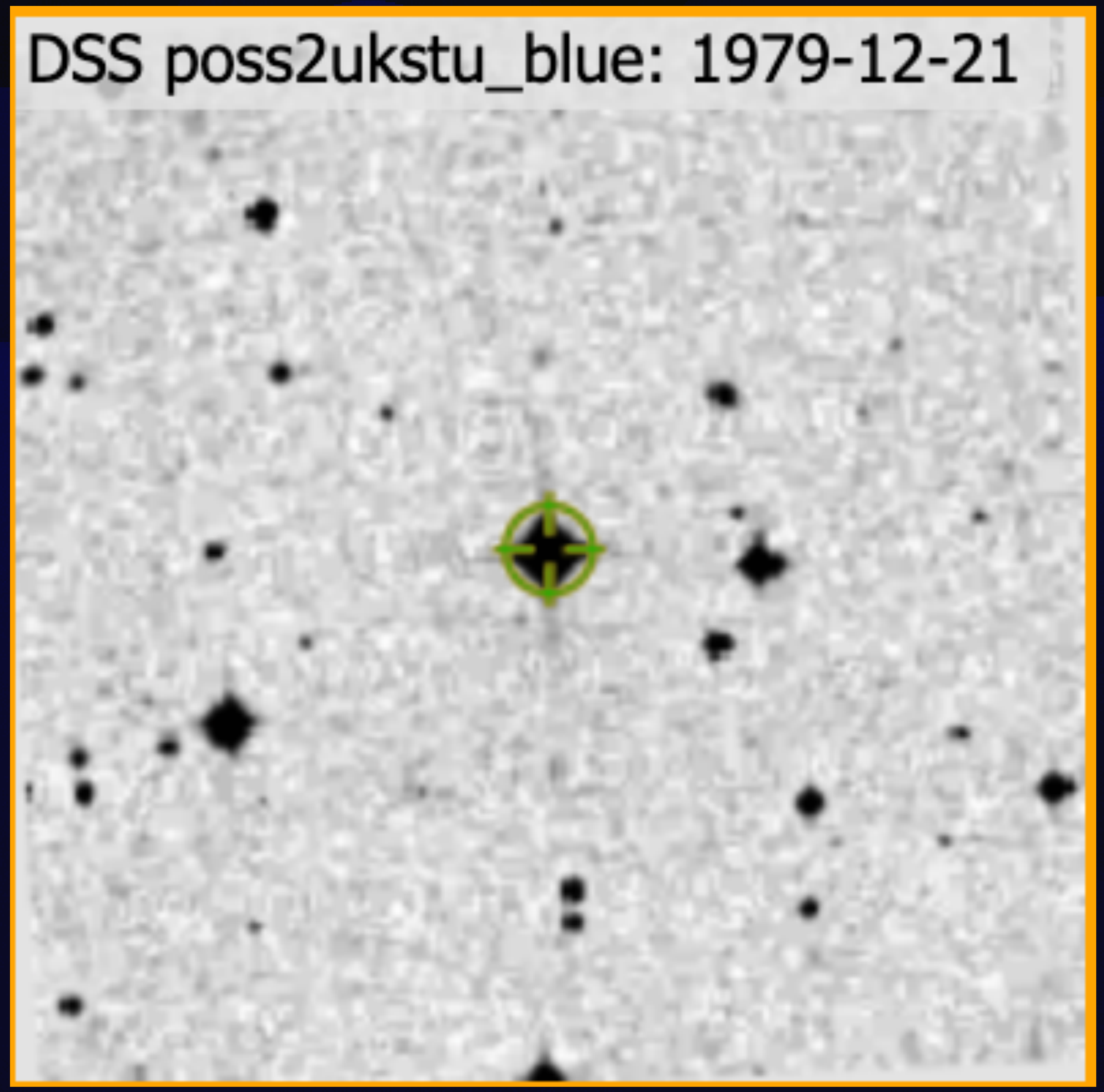
Distance: 2.64 pc (8.6 ly)

Blue-ish giant & WD binary (WD is post-MS)

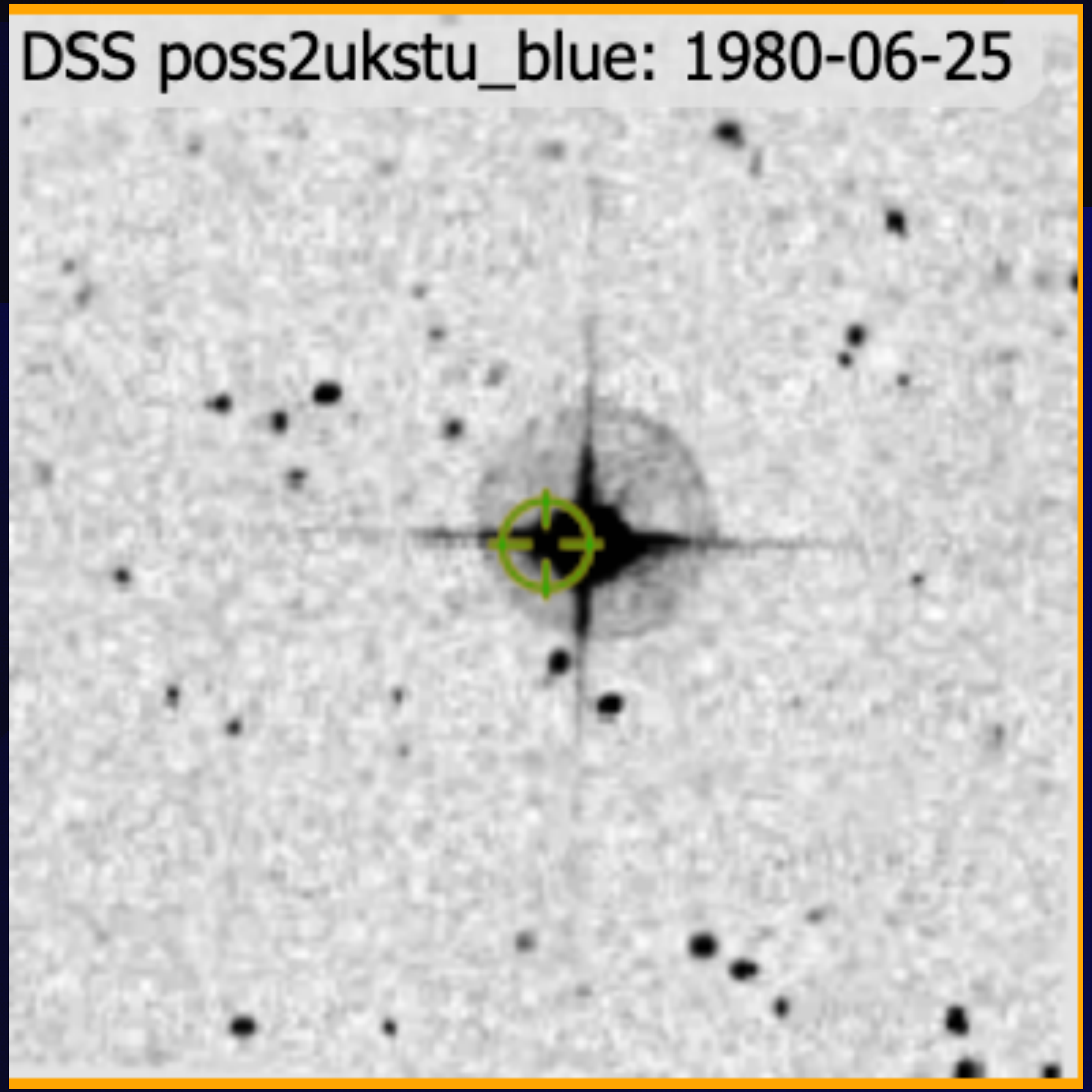
50 yr eccentric orbit

Is this a binary?

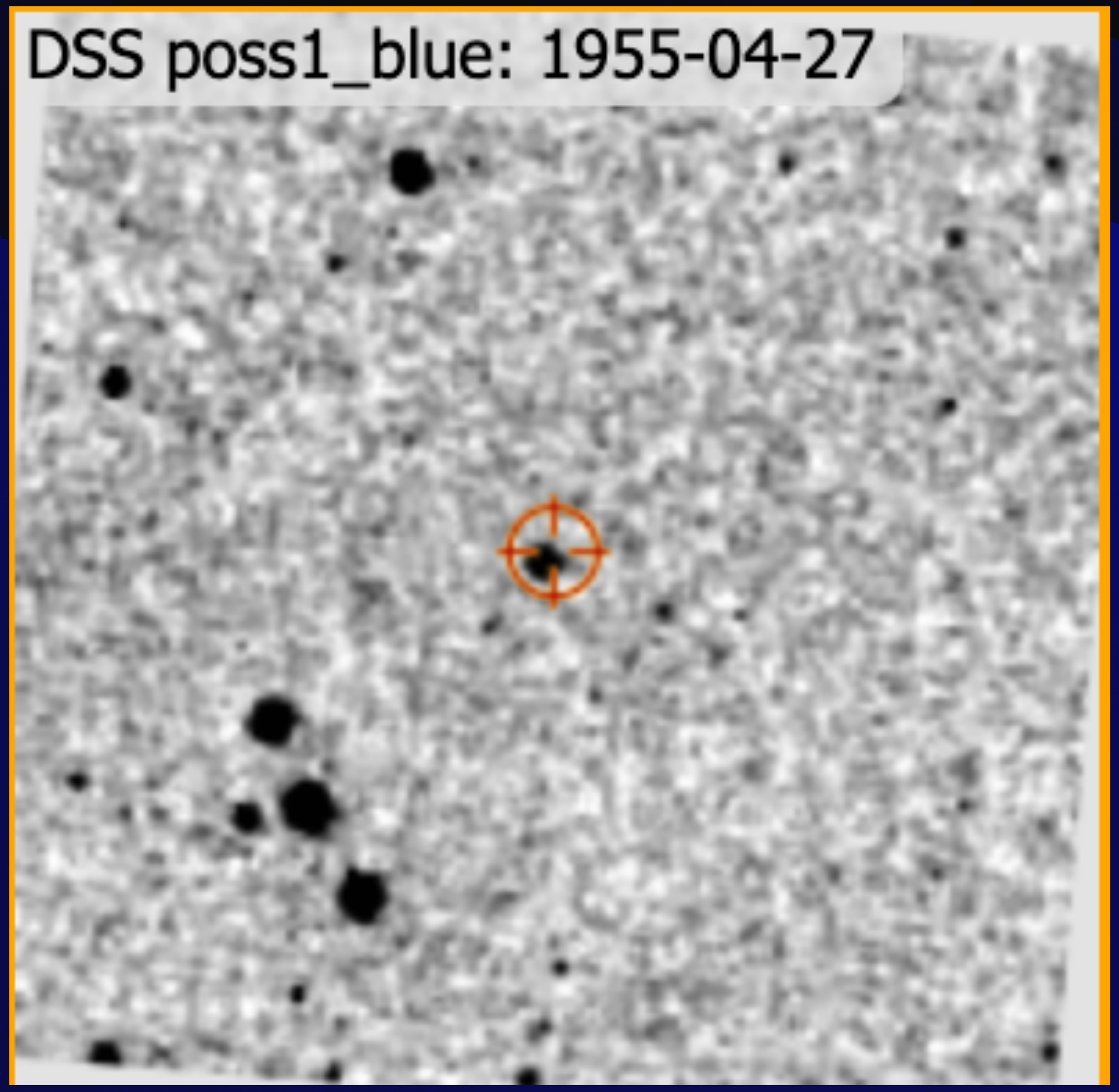
Sometimes it's hard to tell!



TOI 1338
(TESS's first CBP host)



TOI 118
(exoplanet host)



CM Drac

Eclipsing binary stars

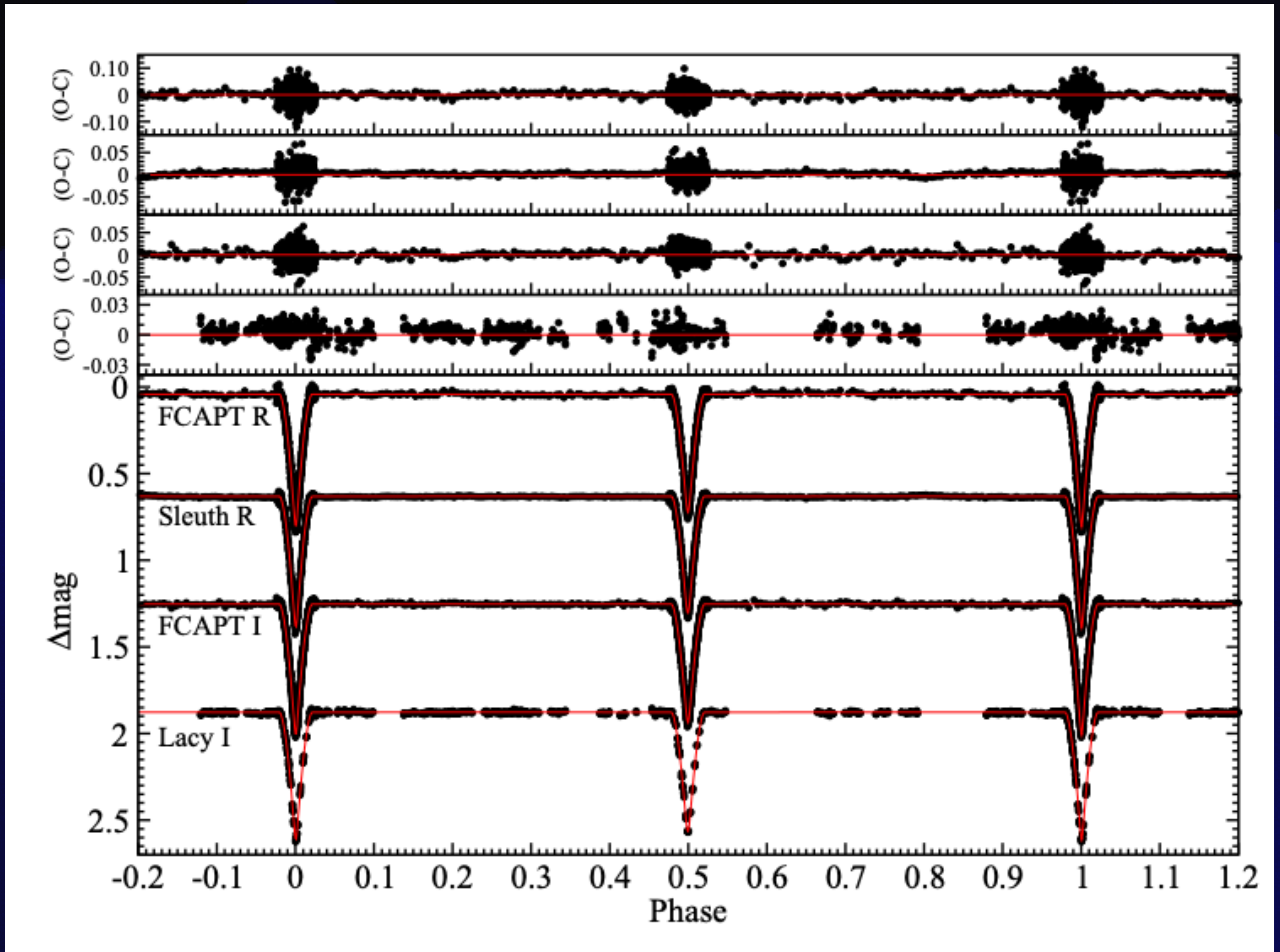
Important constraints in stellar models

Eclipsing binaries offer a glimpse into:

- ✳ Fundamental stellar parameters
- ✳ Intergalactic distance scales
- ✳ Calibrations of evolutionary and stellar population theories
- ✳ The world of extrasolar planets, pulsating stars, degenerate remnants, dwarfs and giants
- ✳ The world of ambitious observing surveys
- ✳ Extensive super-computer calculations, big data science
- ✳ And so much more!

Thank you Andrej Prsa for these ideas!

Light curve (LC): time-series flux data



A phase-folded light curve of CM Drac, one of the most well-studied nearby low-mass EBs. Fig copied from Morales et al. (2008)

Eclipses + Transits

$$\text{Depth} = \frac{R_p^2}{R_*^2}$$

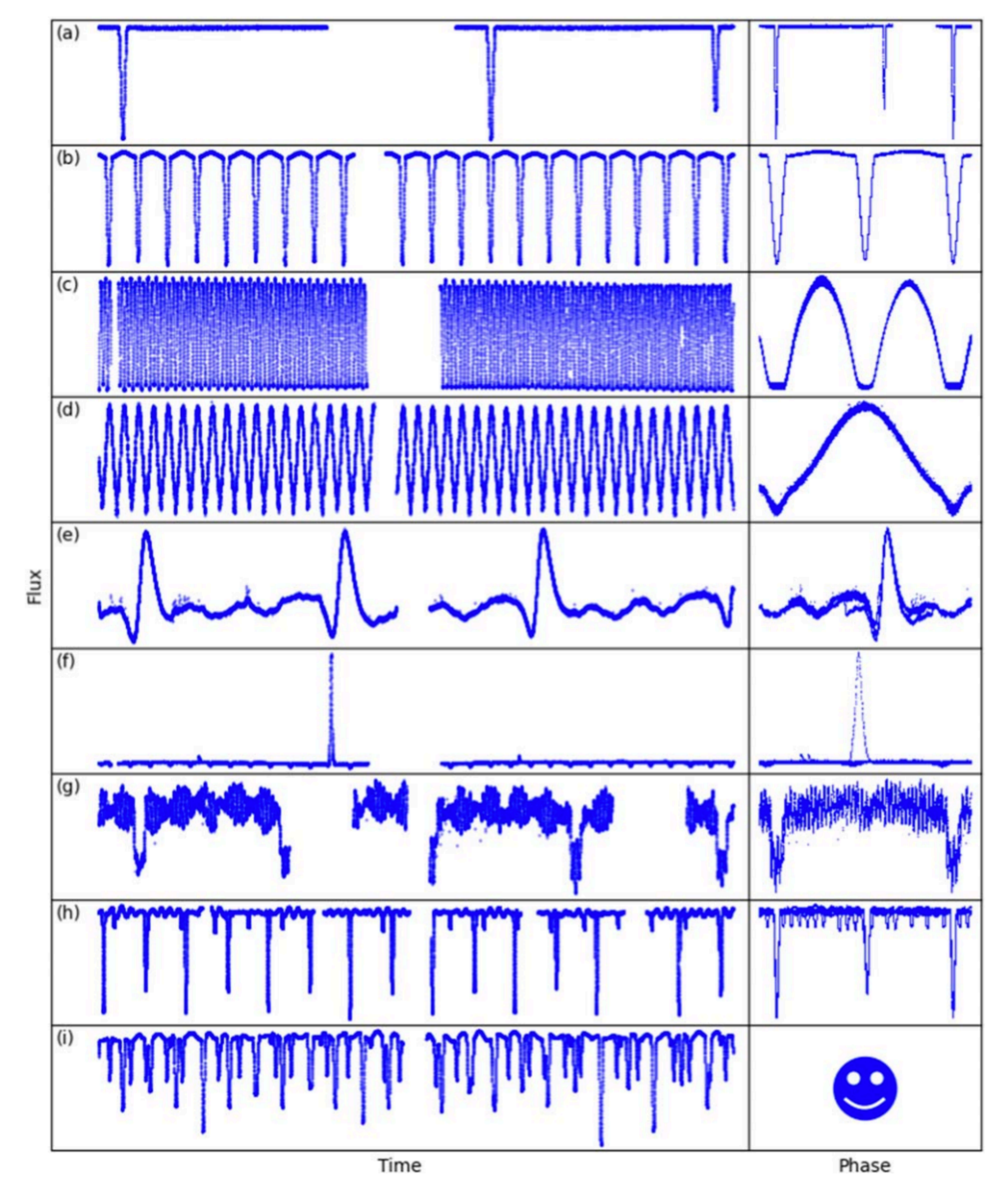
$$b = \frac{a\cos i}{R_*}$$

$$T_{dur} = \frac{P}{\pi}\sin^{-1}\left(\frac{\sqrt{\left(R_* + R_p\right)^2 - (bR_*)^2}}{a}\right)$$

R_p = planet radius
R_* = stellar radius
b = impact parameter
a = semi-major axis
(orbital distance)
i = orbital inclination
P = orbital period

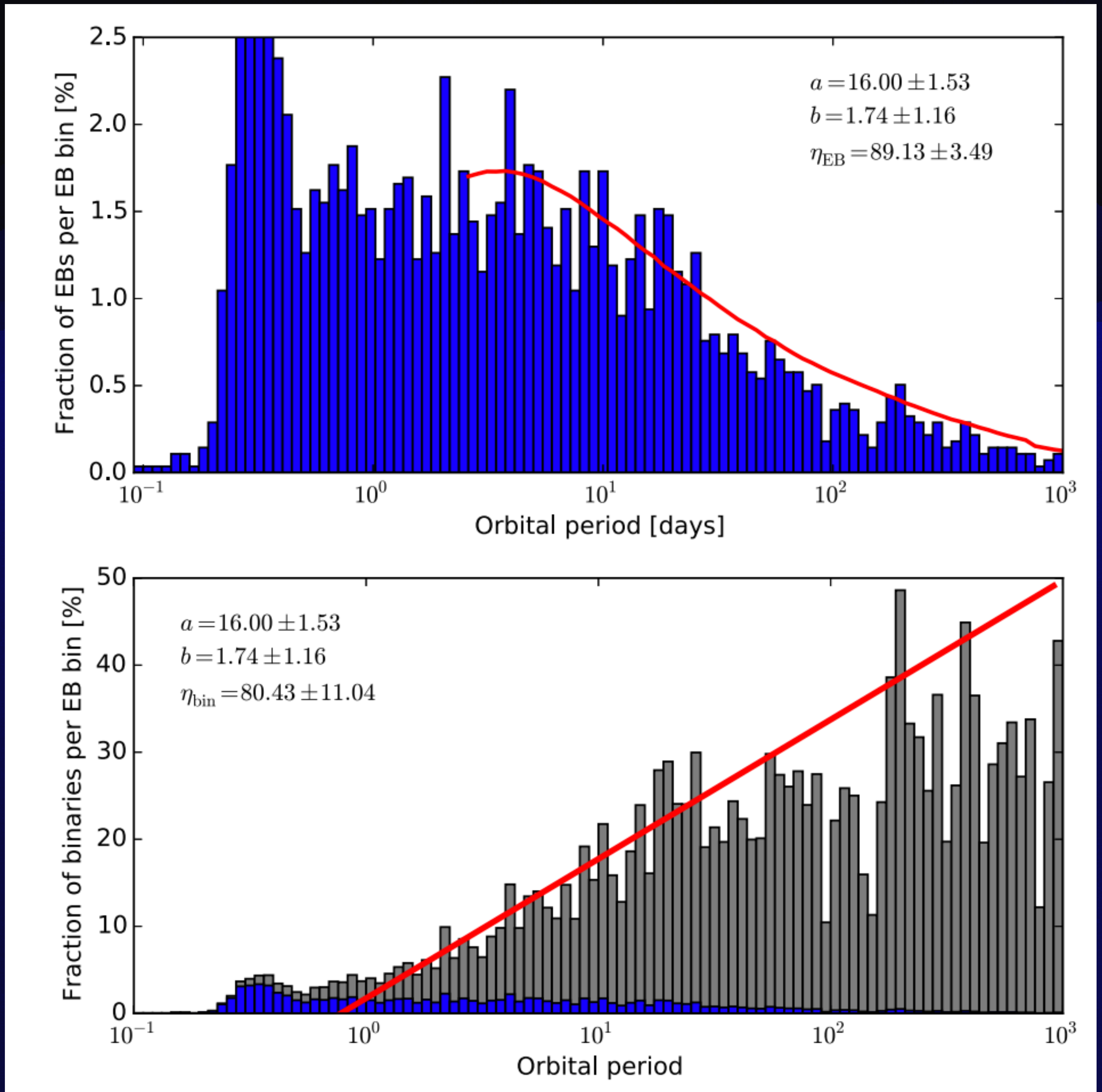
www.eso.org

Eclipsing binaries



Example TESS LCs

Kepler EB orbital period distribution

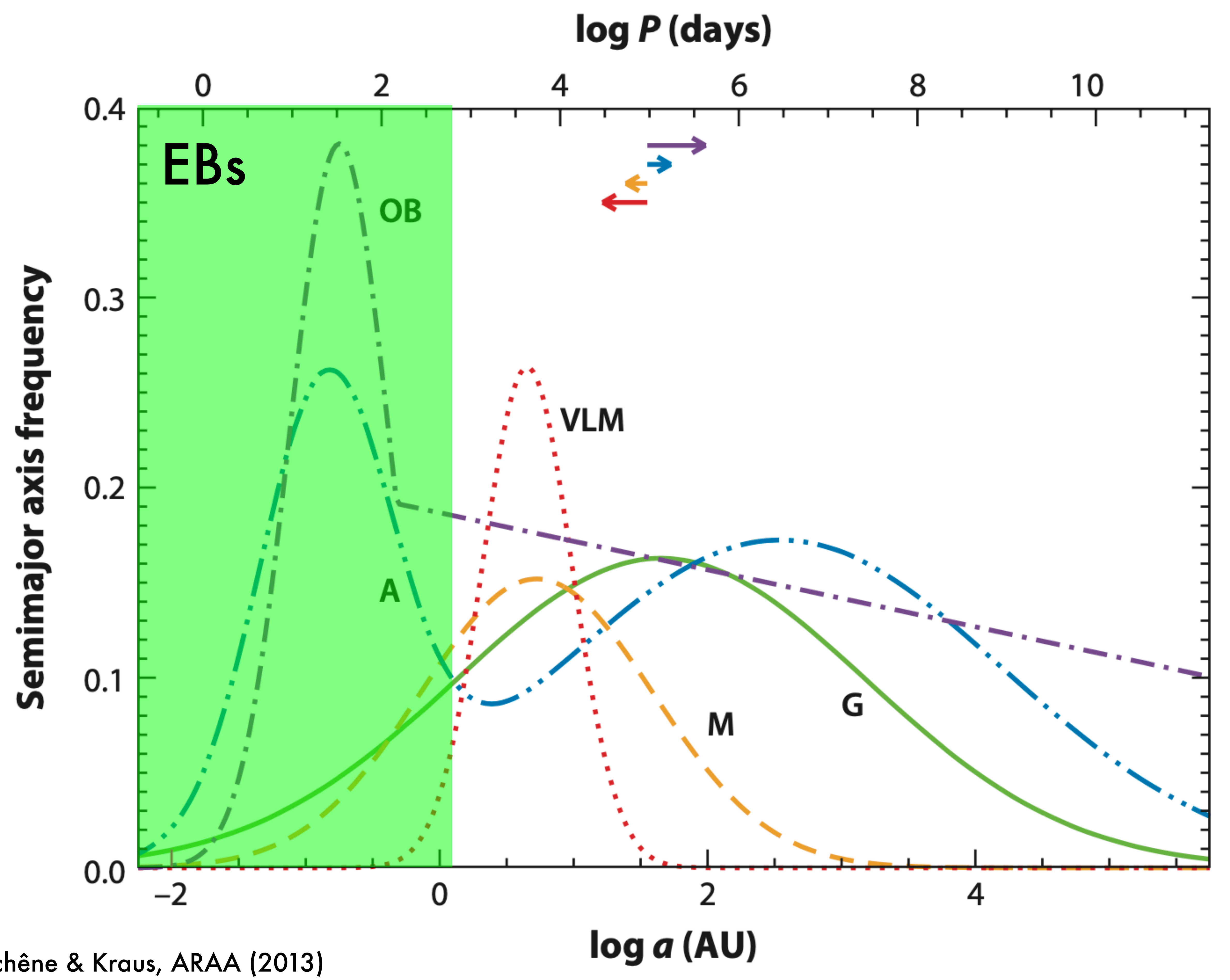


Compare to binary populations

EBs sample a tail of the overall period distribution

Eclipse probability:

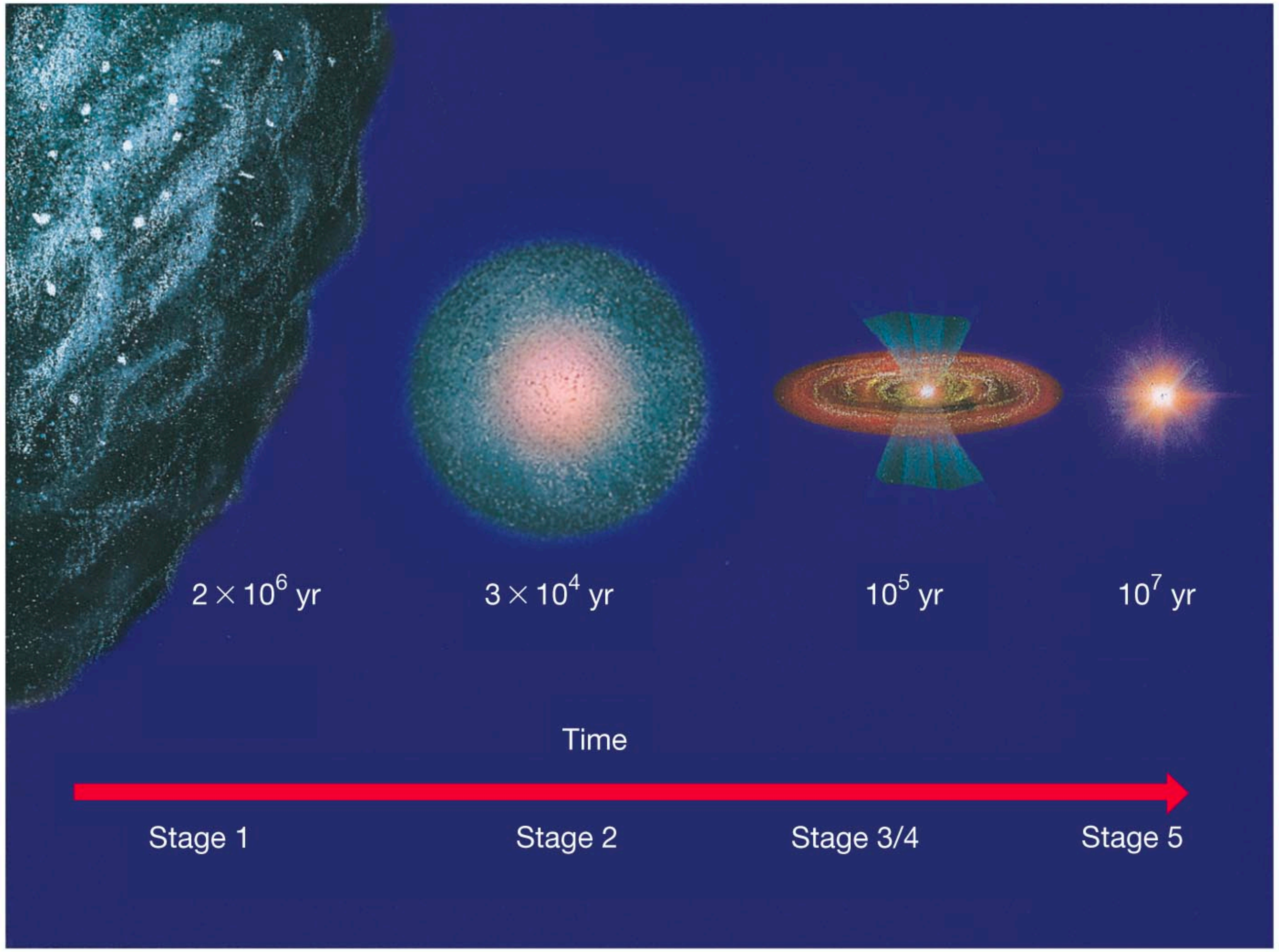
$$Prob \approx \frac{2R_*}{a}$$



Duchêne & Kraus, ARAA (2013)

JAMES WEBB SPACE TELESCOPE

CARINA NEBULA | NGC 3324



NIRCam Filters | F187N F444W F470N

From the Dust

Two stars are born

Tokovinin, A. Architecture of Hierarchical Stellar Systems and Their Formation. *Universe* **2021**, *7*, 352.

What shrinks binary orbits?

Forming binaries on the shortest periods

- Tightest binaries might form via Kozai-Lidov oscillations & tidal friction (KLOTF)
  - Due to influence from hierarchical triple system, which removes angular momentum from tight binary

- Effect on CBPs
  - Will cast CBPs to inclined and eccentric orbits, making them difficult to find

A triple origin for the lack of tight coplanar circumbinary planets around short-period binaries

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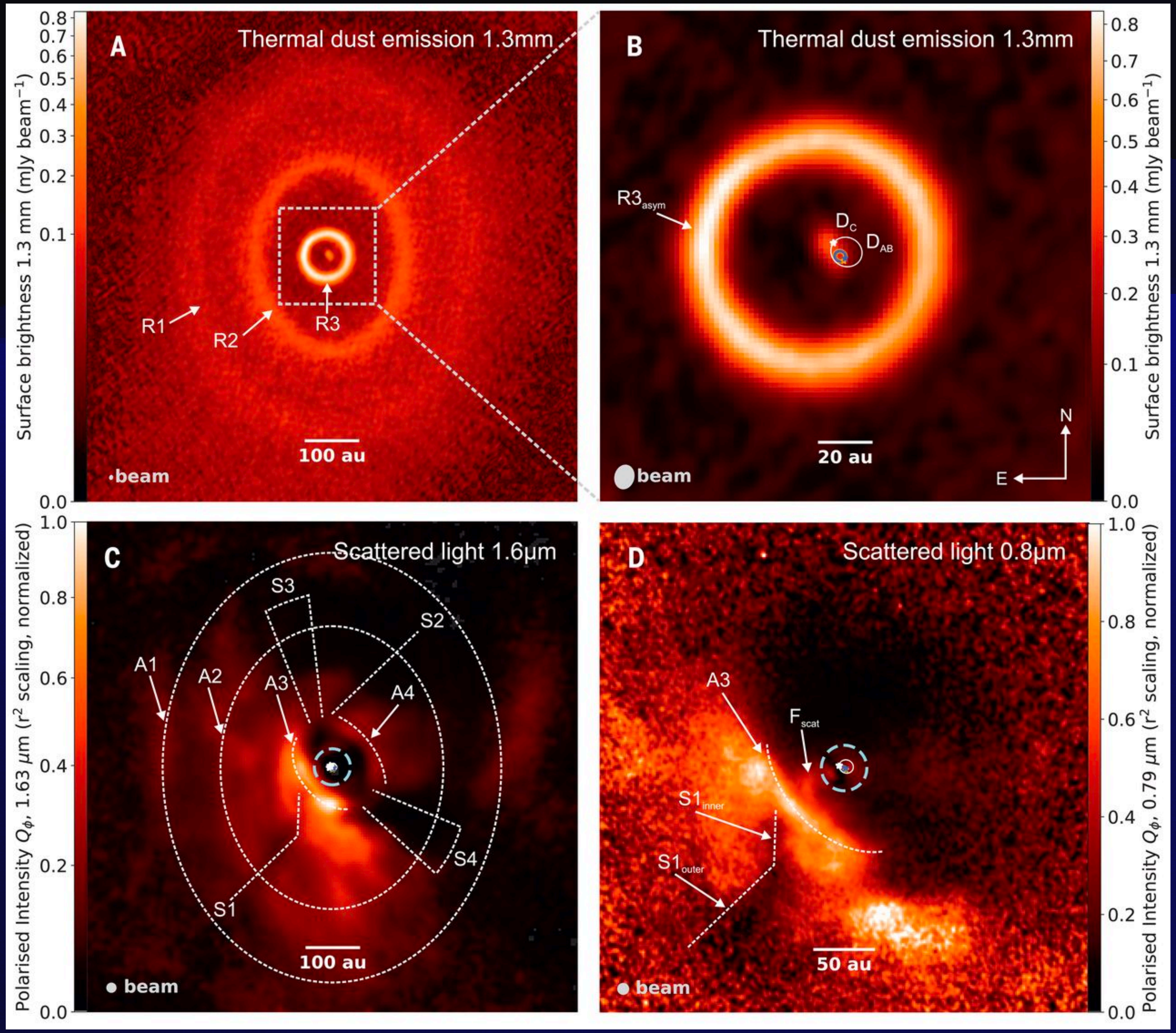


Kraus, S. et al., A triple-star system with a misaligned and warped circumstellar disk shaped by disk tearing. (2020).

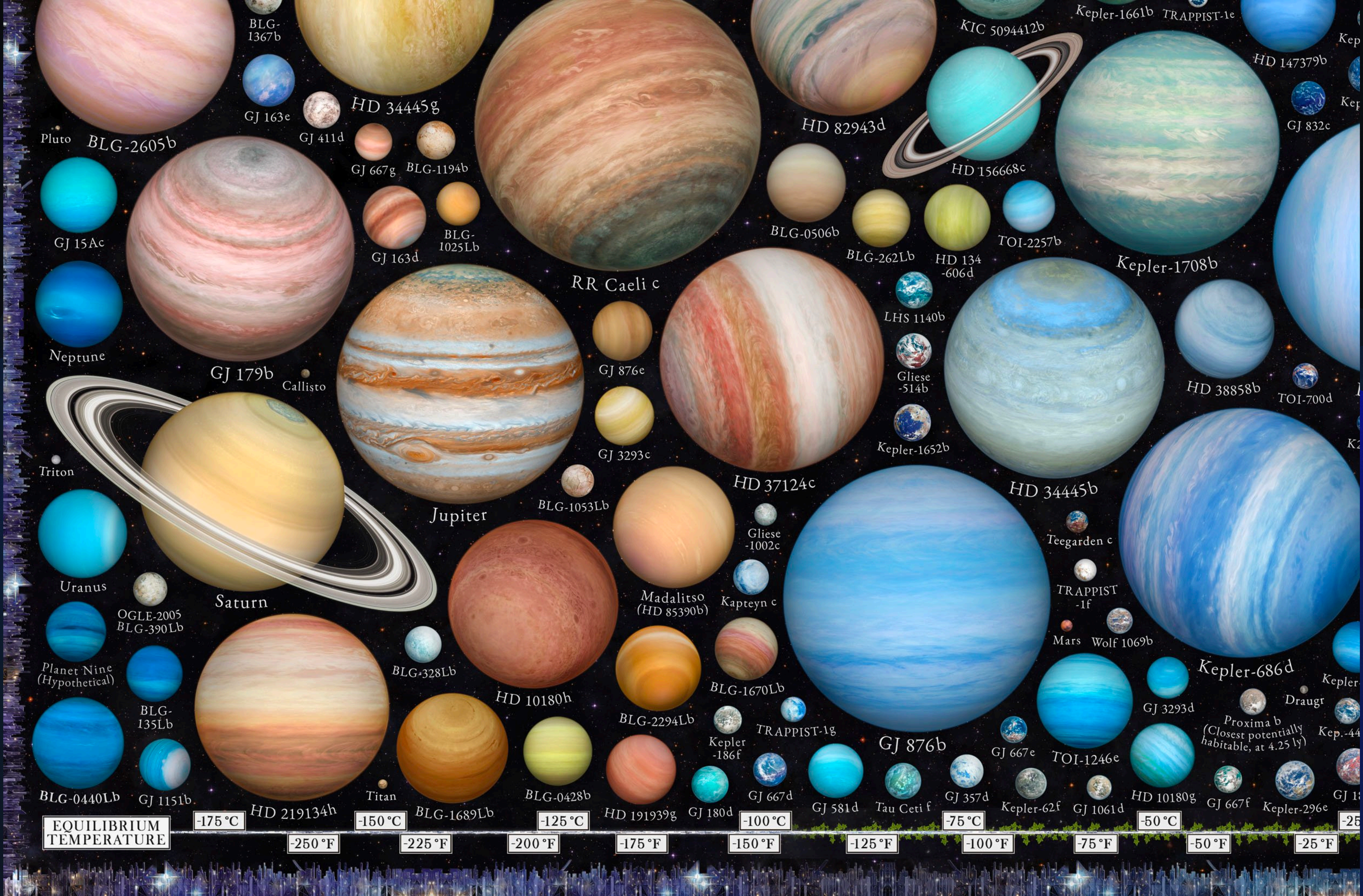
Quick recap

* Binaries are more common than you might think, and are an important part of our galactic zoo of stars
  * They're even more common for higher-mass stars

* Eclipsing binaries yield a LOT of science, including model-independent stellar parameters

* Tight binaries form via:
  - Disk fragmentation
  - Core/turbulence mediated
  - N-body interactions

* The tightest binaries form via KLOTF


BLG-1367b
GJ 163e
HD 34445g
GJ 411d
Pluto
BLG-2605b
GJ 667g
BLG-1194b
KIC 5094412b
Kepler-1661b
TRAPPIST-1e
HD 147379b
GJ 832c
HD 82943d
HD 156668c
GJ 15Ac
GJ 163d
BLG-1025Lb
BLG-0506b
BLG-262Lb
HD 134-606d
TOI-2257b
Kepler-1708b
RR Caeli c
Neptune
GJ 179b
Callisto
LHS 1140b
Gliese-514b
HD 38858b
TOI-700d
GJ 876e
GJ 3293c
Kepler-1652b
HD 37124c
HD 34445b
Triton
Jupiter
BLG-1053Lb
Gliese-1002c
Teegarden c
Uranus
Saturn
OGLE-2005 BLG-390Lb
Madalitso (HD 85390b)
Kapteyn c
TRAPPIST-1f
Mars
Wolf 1069b
Kepler-686d
Planet Nine (Hypothetical)
BLG-135Lb
BLG-328Lb
HD 10180h
BLG-1670Lb
GJ 3293d
Draugr
Proxima b (Closest potentially habitable, at 4.25 ly)
BLG-2294Lb
TRAPPIST-1g
Kepler-186f
GJ 876b
GJ 667e
TOI-1246e
BLG-0440Lb
GJ 1151b
Titan
HD 219134h
BLG-1689Lb
BLG-0428b
HD 191939g
GJ 180d
GJ 667d
GJ 581d
Tau Ceti f
GJ 357d
Kepler-62f
GJ 1061d
HD 10180g
GJ 667f
Kepler-296e
EQUILIBRIUM TEMPERATURE
-175 °C
-150 °C
-125 °C
-100 °C
-75 °C
-50 °C
-250 °F
-225 °F
-200 °F
-175 °F
-150 °F
-125 °F
-100 °F
-75 °F
-50 °F
-25 °F

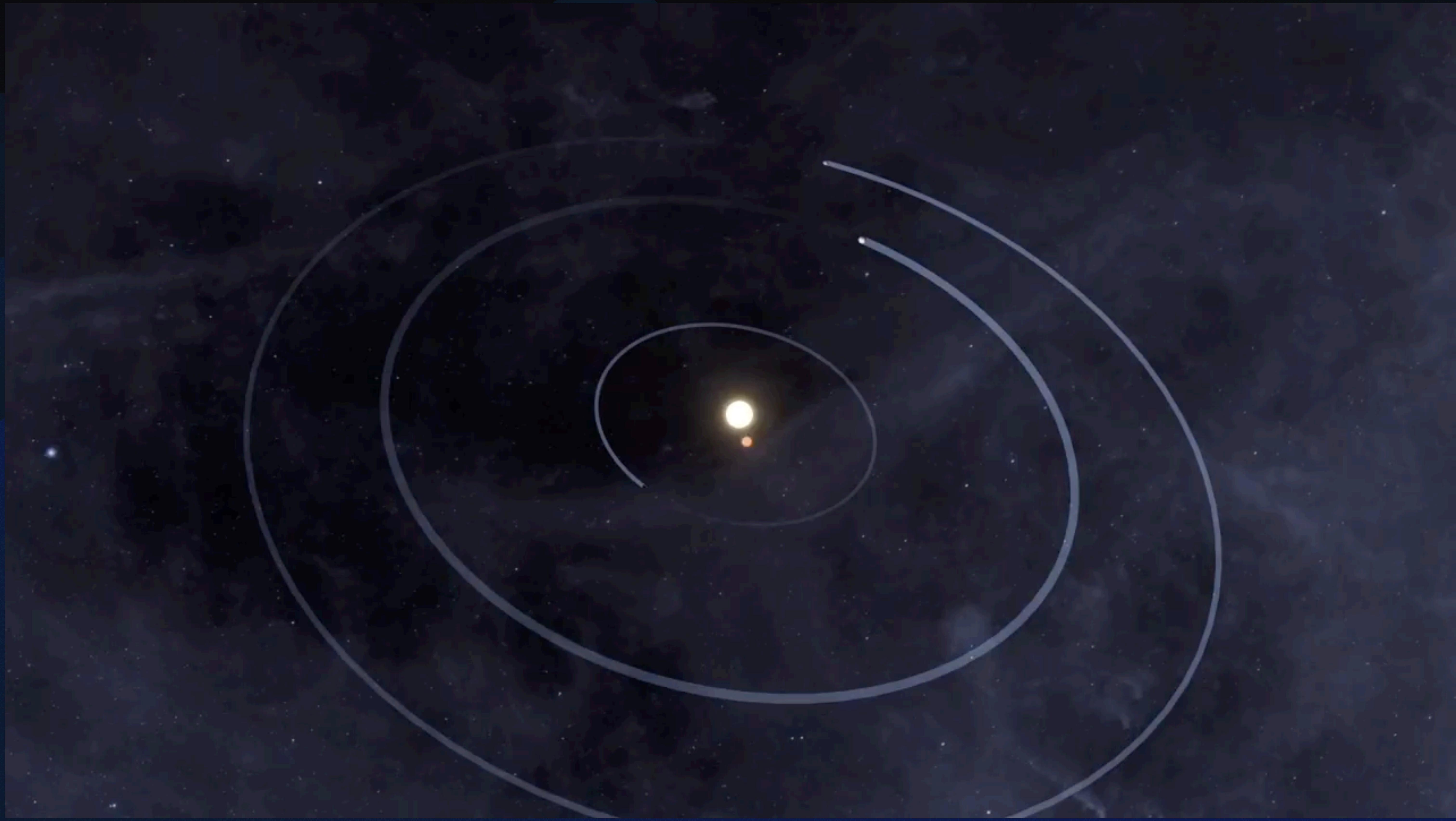
Circumbinary Systems

Planets orbiting two stars

Example: Kepler-47 system

- Binary: circular 7.4d orbit
  - Primary: solar-like star
  - Secondary: smaller M-dwarf star

- Three planets!
  - Inner planet: sub-Neptune with a ~50d orbital period
  - Middle planet: Saturn-sized with a ~190d orbital period
  - Outer planet: Uranus-sized with a ~300d period

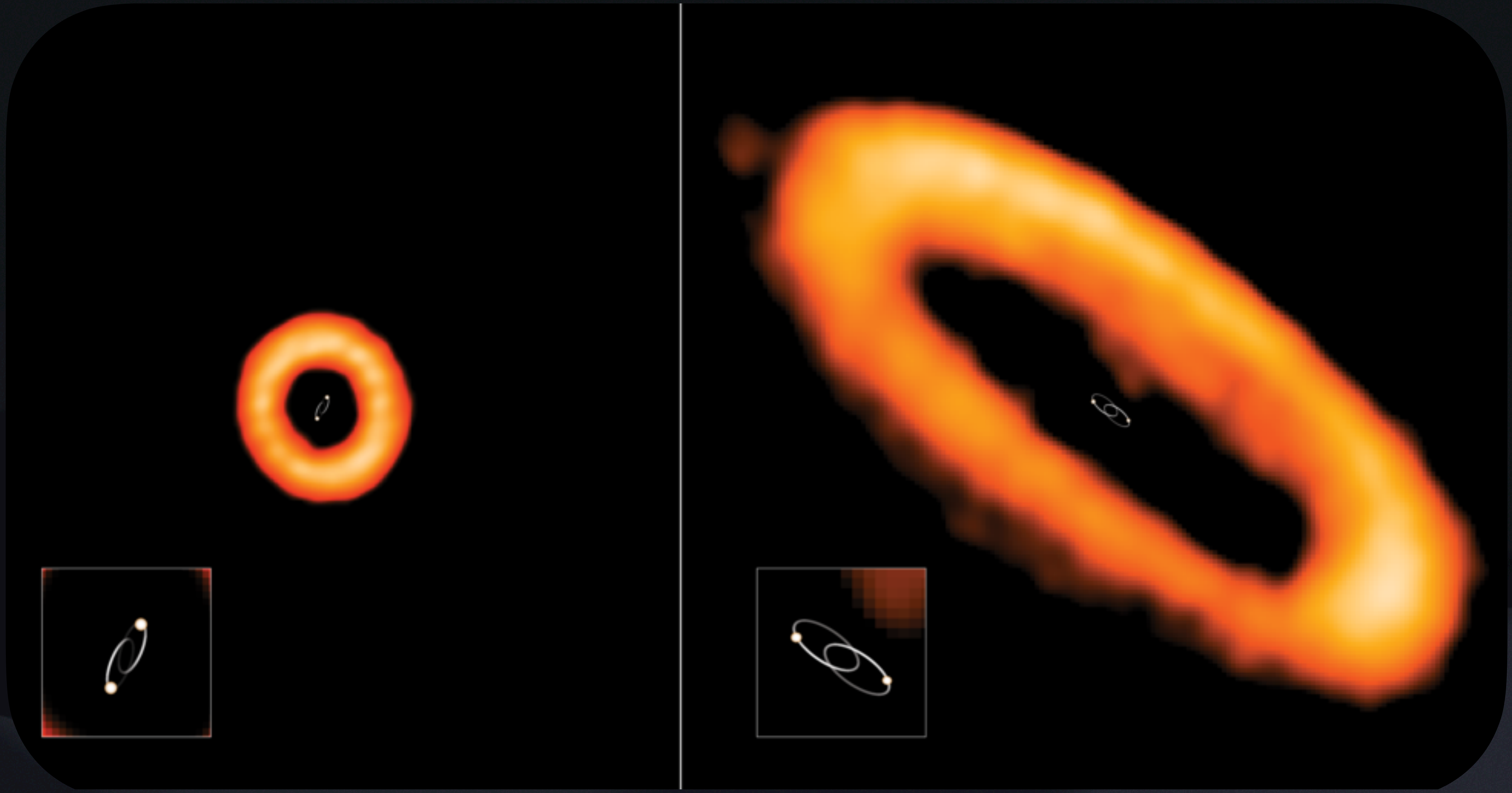


VideofromSpace channel on Youtube

CBP formation

Central cavities, dynamic inner disks, but sorta normal

- ✳Binaries carve central cavities, restricting close orbits
- ✳Beyond cavity, binaries make planet formation nightmarish in inner disk
- ✳Likely smooth sailing in the outer disk, but possibly less material, unless actively accreting



Forming CBPs

easy…right?

- Circumbinary disks tend to be hostile to planet formation
  - Torques and tides
  - High eccentricities and relative velocities —> more often leads to breaking than sticking collisions
  - Magnetorotational instabilities
  - Oh My!

- Tight binary stars might disperse their disks more quickly than single stars, giving planets less time to form

HOW NOT TO BUILD TATOOINE: THE DIFFICULTY OF IN SITU FORMATION OF CIRCUMBINARY PLANETS KEPLER 16b, KEPLER 34b, AND KEPLER 35b

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Received 2012 May 2; accepted 2012 June 14; published 2012 July 9

ABSTRACT

We study planetesimal evolution in circumbinary disks, focusing on the three systems Kepler 16, 34, and 35 where planets have been discovered recently. We show that for circumbinary planetesimals, in addition to secular forcing, eccentricities evolve on a dynamical timescale, which leads to orbital crossings even in the presence of gas drag. This makes the current locations of the circumbinary Kepler planets hostile to planetesimal accretion. We then present results from simulations including planetesimal formation and dust accretion, and show that even in the most favorable case of 100% efficient dust accretion, in situ growth starting from planetesimals smaller than ~10 km is difficult for Kepler 16b, Kepler 34b, and Kepler 35b. These planets were likely assembled further out in the disk, and migrated inward to their current location.

Key word: planets and satellites: formation

THE ROLE OF MULTIPLICITY IN DISK EVOLUTION AND PLANET FORMATION

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Received 2011 January 21; accepted 2011 September 17; published 2011 December 28

ABSTRACT

The past decade has seen a revolution in our understanding of protoplanetary disk evolution and planet formation in single-star systems. However, the majority of solar-type stars form in binary systems, so the impact of binary companions on protoplanetary disks is an important element in our understanding of planet formation. We have compiled a combined multiplicity/disk census of Taurus–Auriga, plus a restricted sample of close binaries in other regions, in order to explore the role of multiplicity in disk evolution. Our results imply that the tidal influence of a close ($\lesssim$40 AU) binary companion significantly hastens the process of protoplanetary disk dispersal, as ~2/3 of all close binaries promptly disperse their disks within $\lesssim$1 Myr after formation. However, prompt disk dispersal only occurs for a small fraction of wide binaries and single stars, with ~80%–90% retaining their disks for at least ~2–3 Myr (but rarely for more than ~5 Myr). Our new constraints on the disk clearing timescale have significant implications for giant planet formation; most single stars have 3–5 Myr within which to form giant planets, whereas most close binary systems would have to form giant planets within $\lesssim$1 Myr. If core accretion is the primary mode for giant planet formation, then gas giants in close binaries should be rare. Conversely, since almost all single stars have a similar period of time within which to form gas giants, their relative rarity in radial velocity (RV) surveys indicates either that the giant planet formation timescale is very well matched to the disk dispersal timescale or that features beyond the disk lifetime set the likelihood of giant planet formation.

Key words: binaries: close – binaries: visual – planets and satellites: formation – protoplanetary disks – stars: formation – stars: pre-main sequence

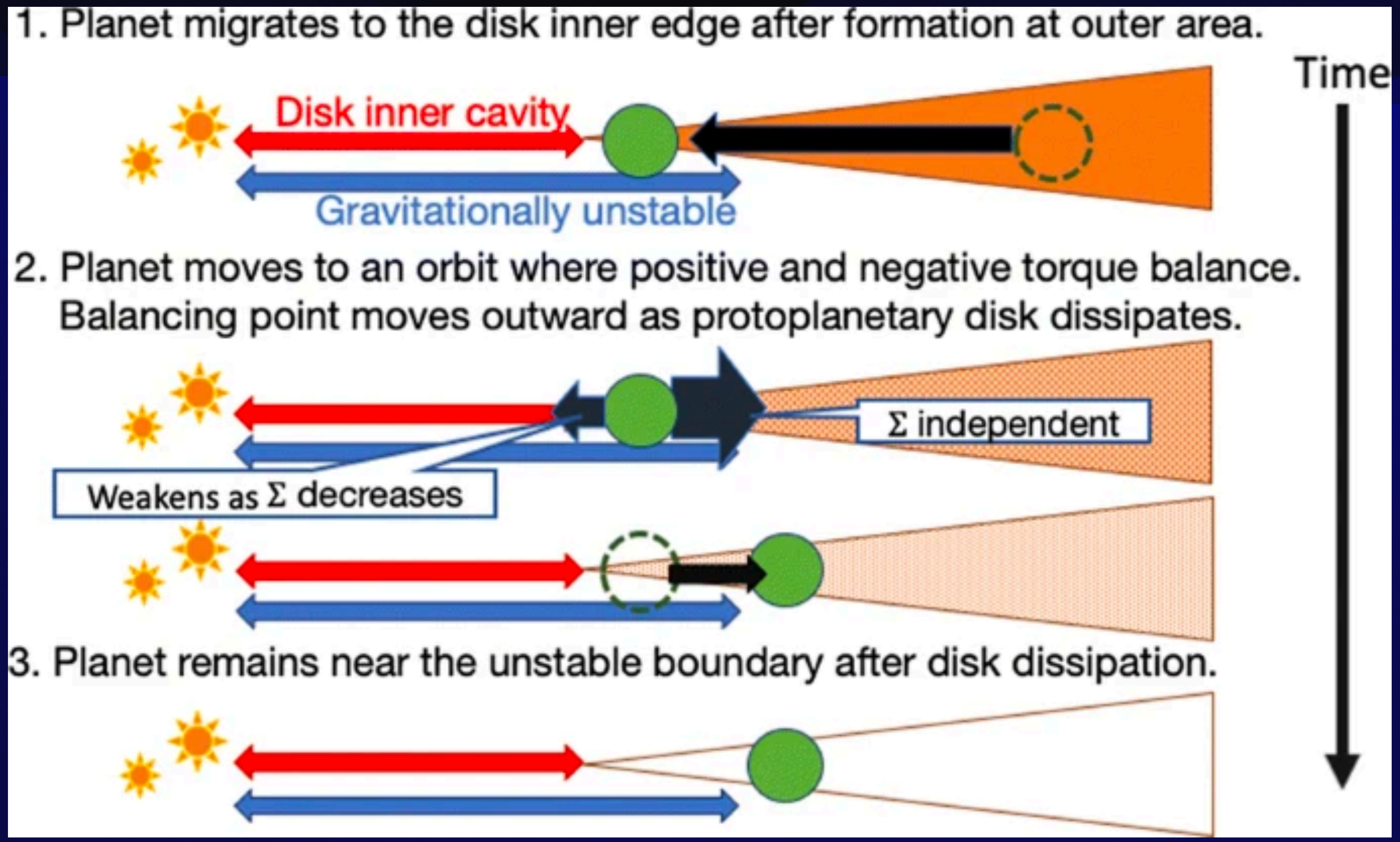
Forming CBPs

How DOES it work? —> migration!

- Things are more stable farther from the binary—> these regions look similar to single-star systems!

- This means that planets likely form farther out in the disk and then migrate inward

- Migration occurs as a result of torque imbalances, which serve to push the planet inwards



Yamanaka & Sasaki ((2019)

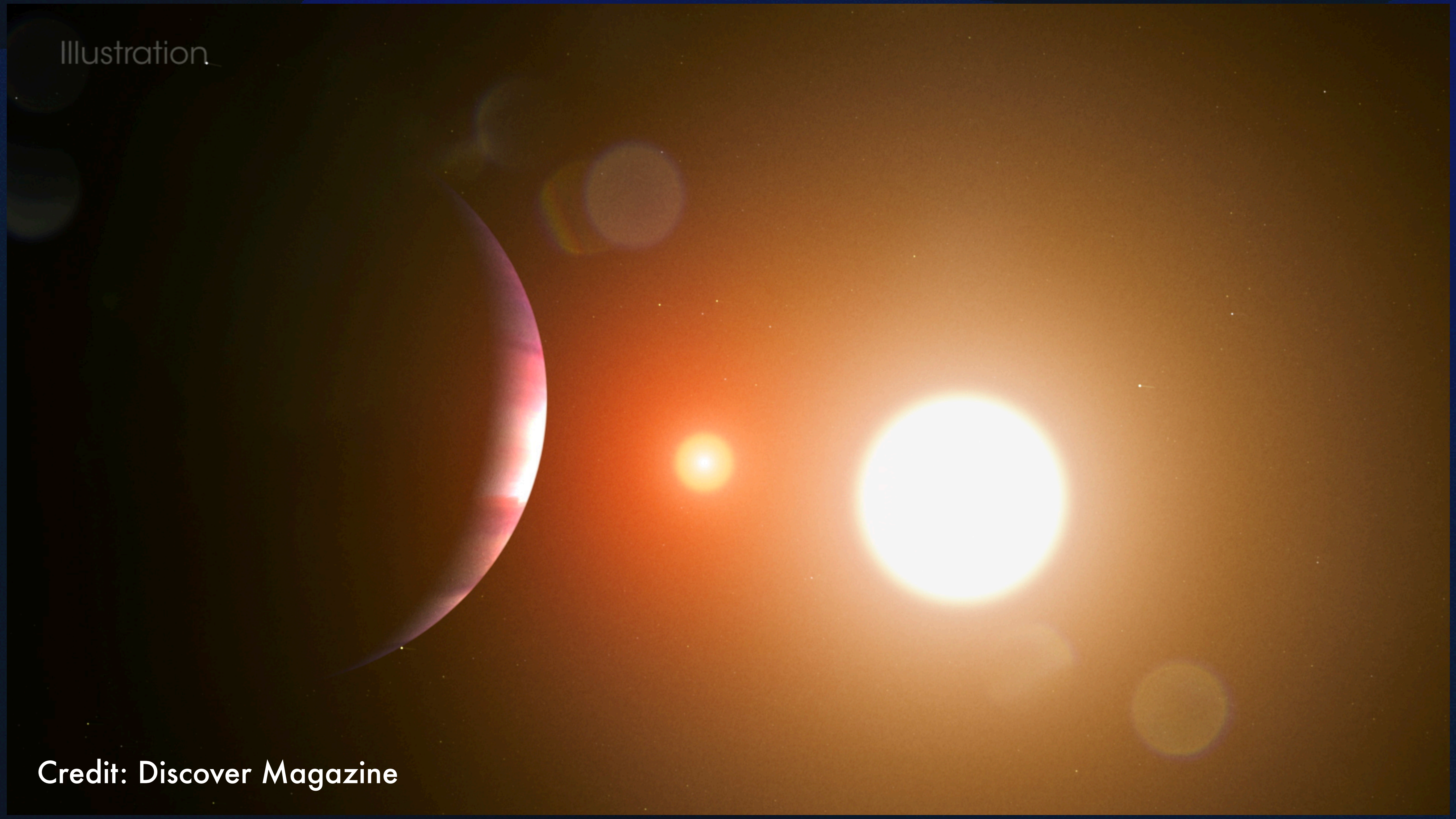
CBPs Exist!

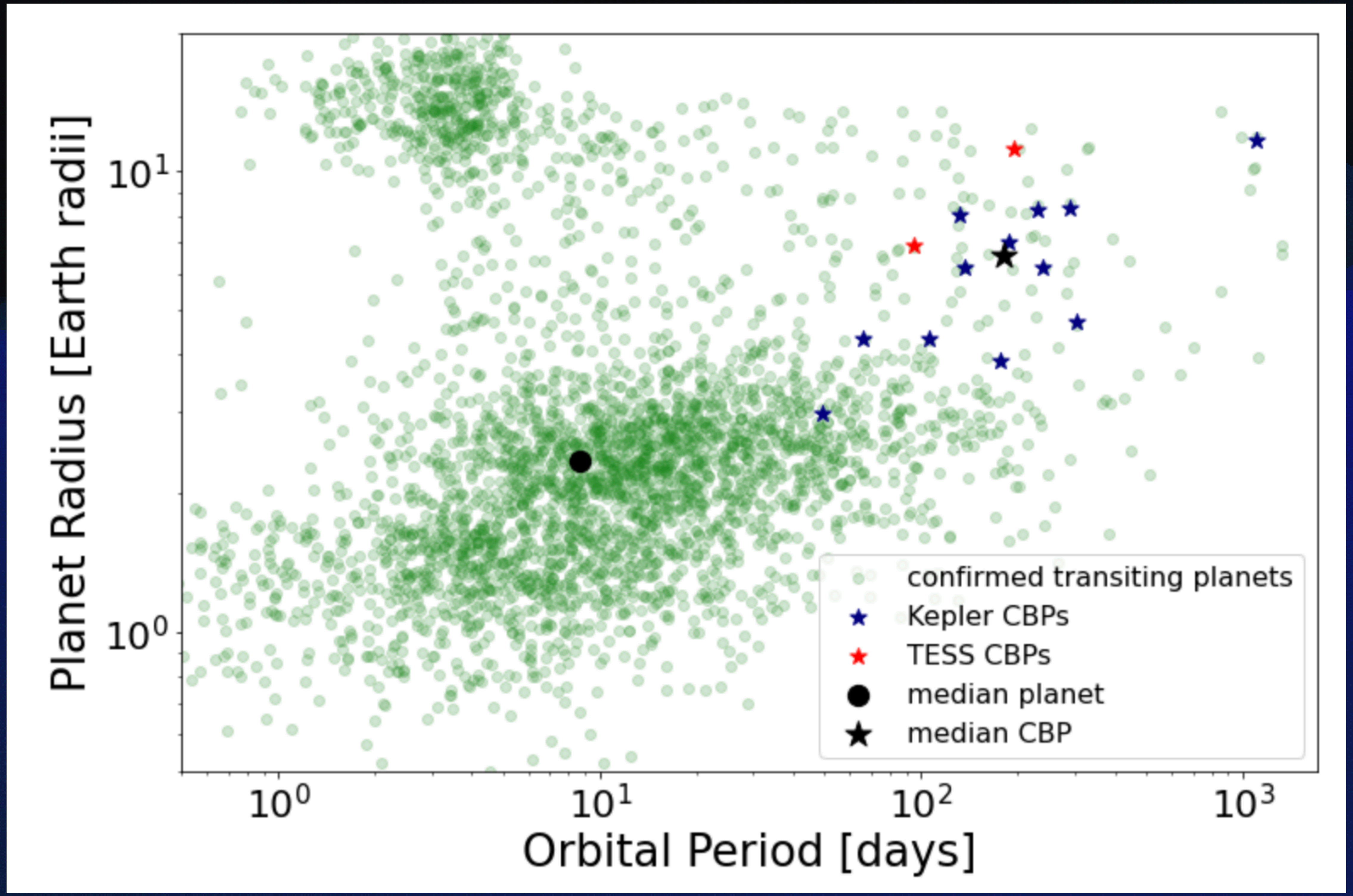
What do we know about them?

What Do We Know So Far?

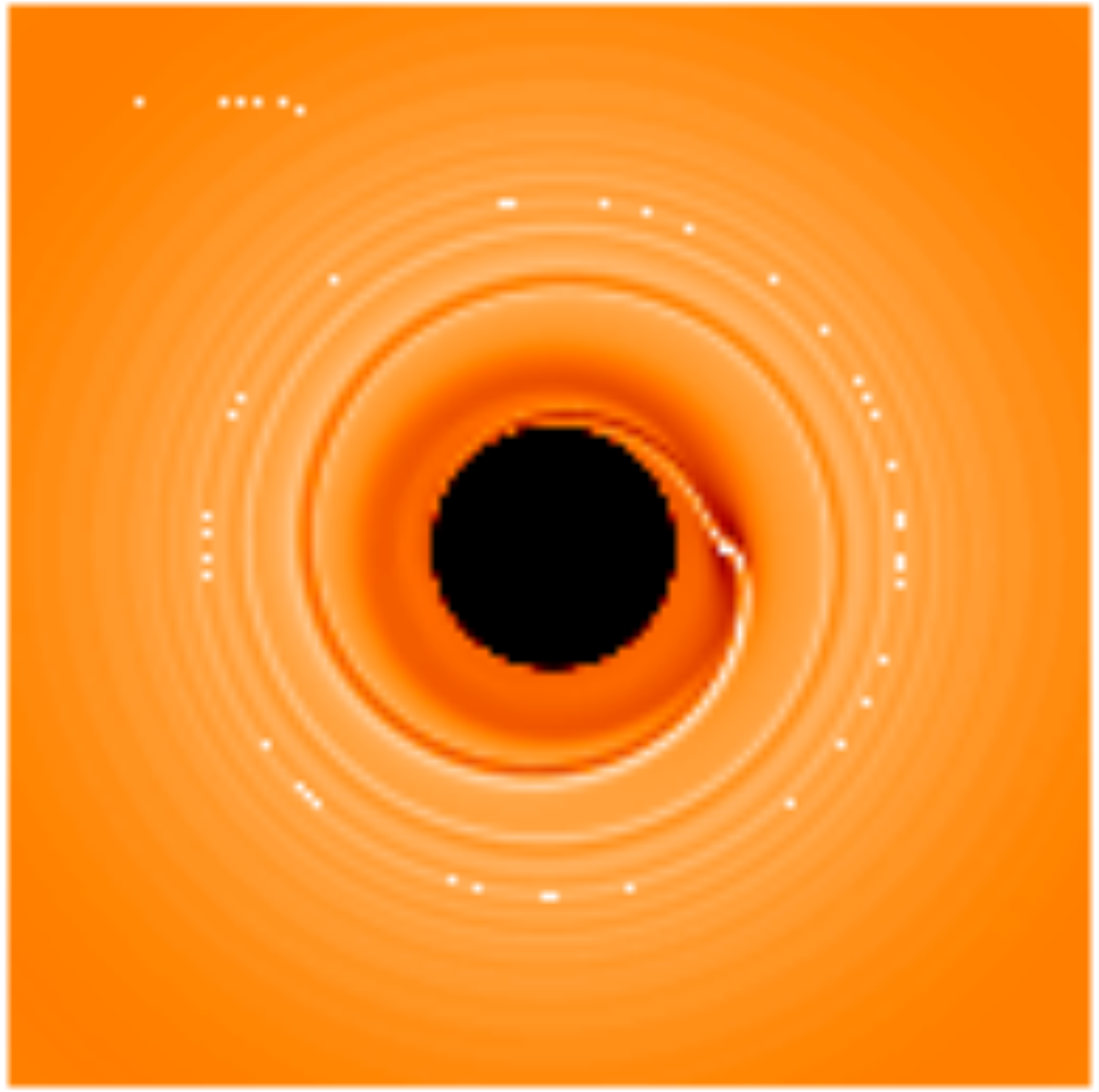
Trends in known CBPs

- CBPs have longer orbital periods and larger radii than most other known planets
  - Bias? Formation? Binaries?

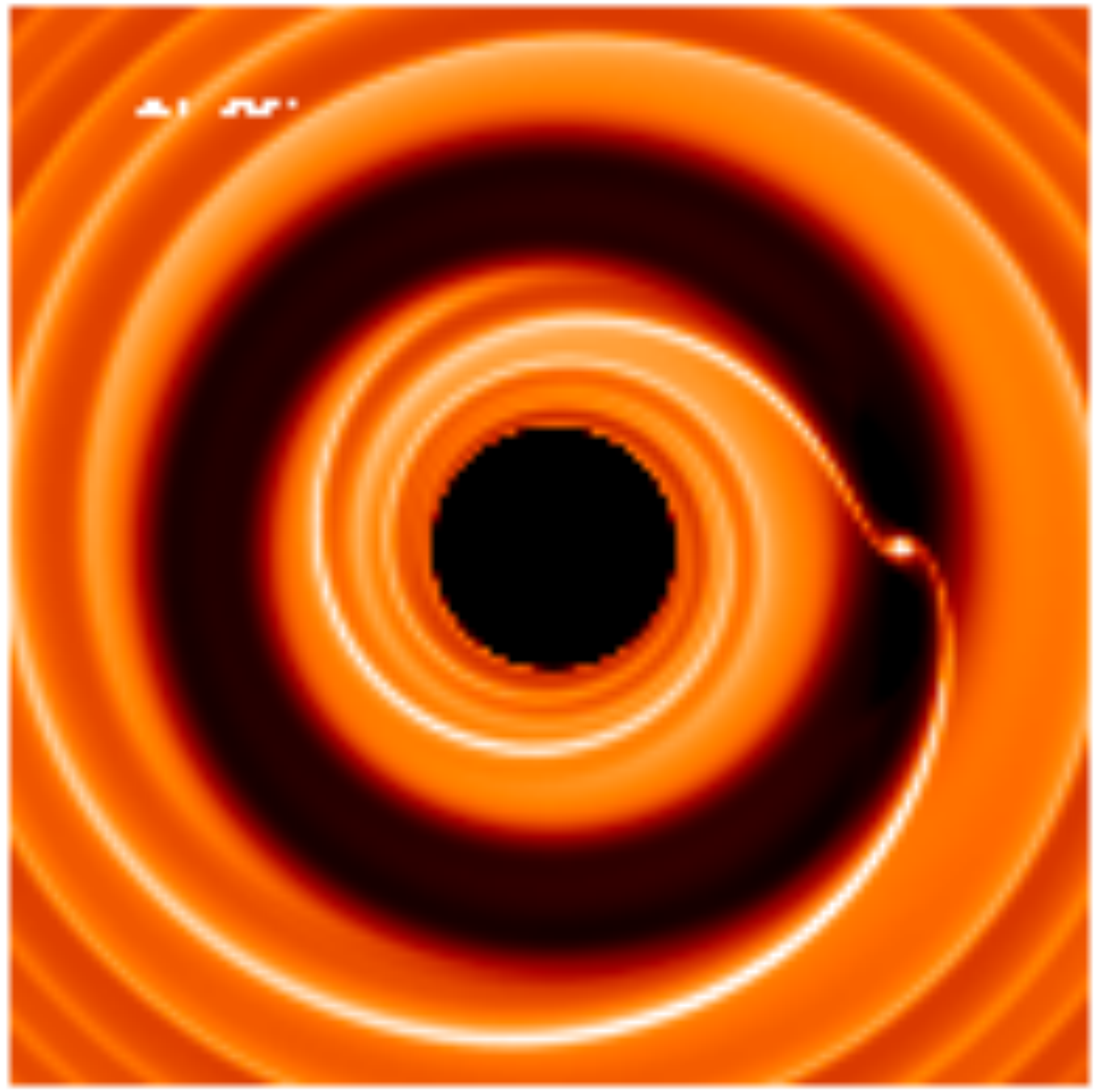




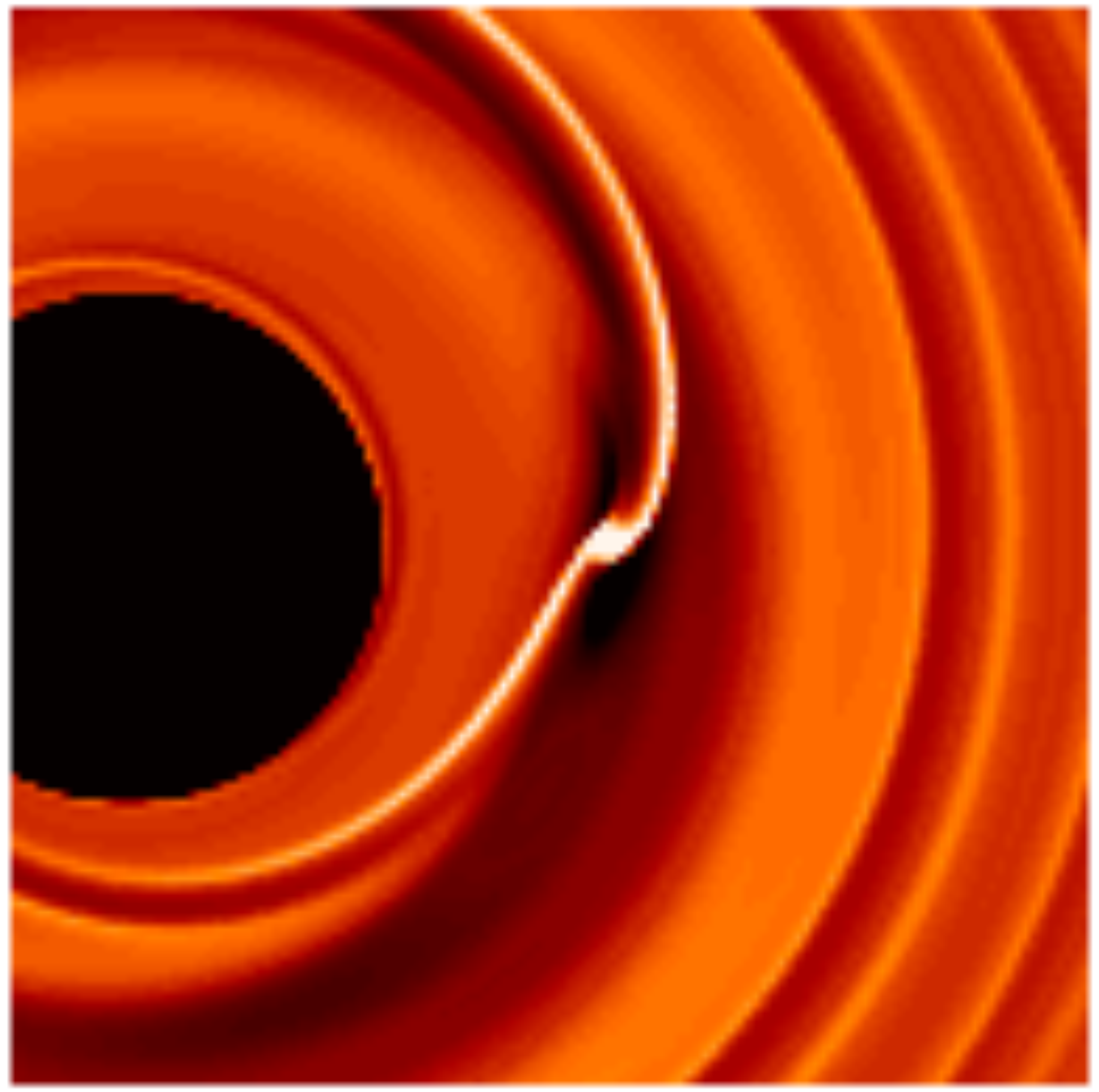
Planet Migration



Type I



Type II



Type III

low-mass planet

a gas driven process in which the planetary disk effectively pushes or pulls the planet to a new position

high-mass planet

happens when the planet is massive enough to open a gap in the disc so that a flow barrier to the disc gas may be established. Type II migration is usually inwards.

due to tidal forces, which mainly occur between the star and the planet and tend to result in more circular orbits.

All Aboard! Migration Station

A pileup as evidence for orbital migration

- Many CBPs have been found near their stability limits for their respective binary: is this real or is this bias?
  - It's not bias, it's consistent with a log-uniform distribution of periods (Li, Holman, & Tao 2016)
  - Could be no pile-up at all, just change how you define stability (Quarles et al., 2018)
- If this is confirmed as a real trait of this population, it is further evidence of the importance of orbital migration in these systems

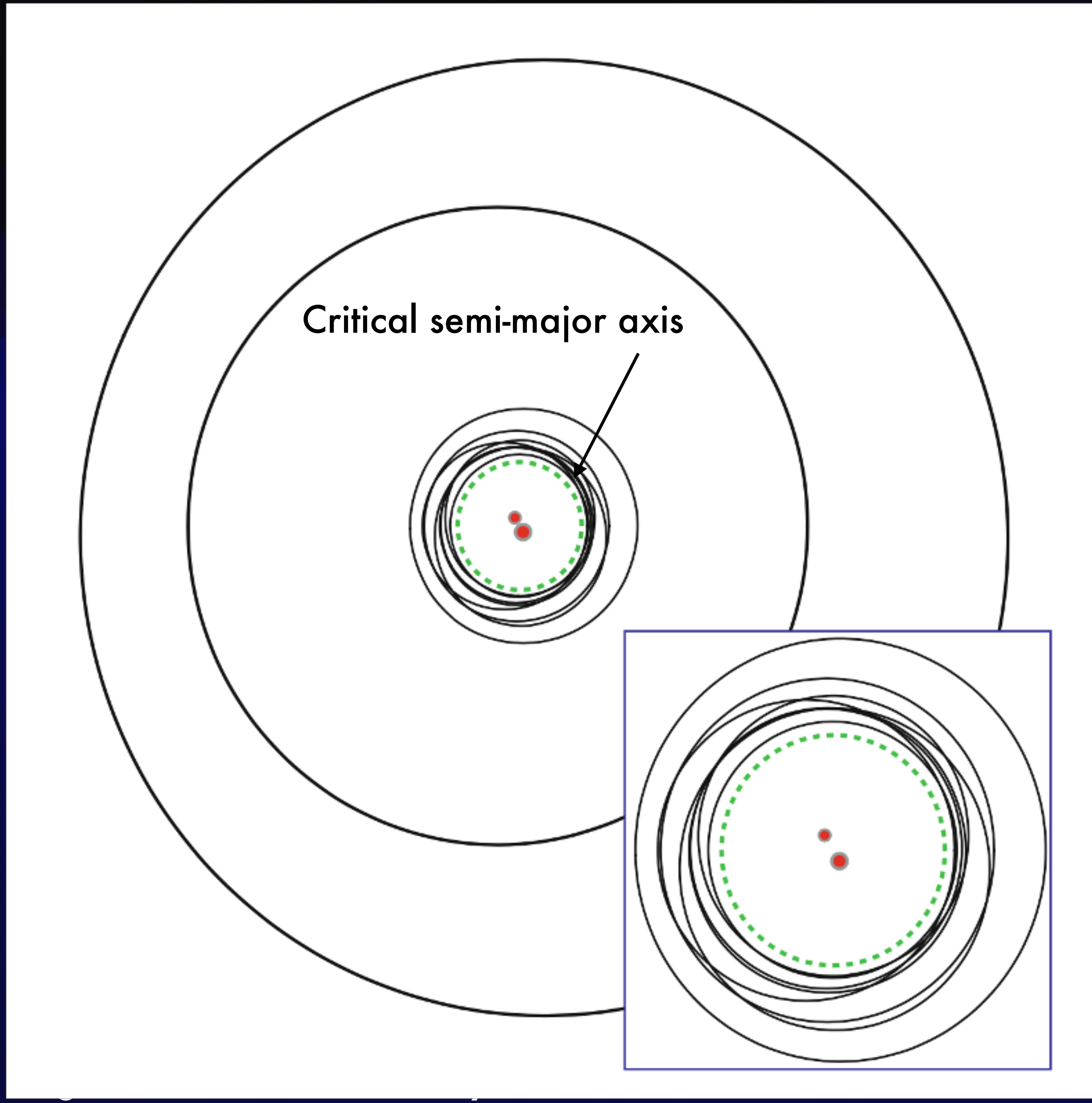


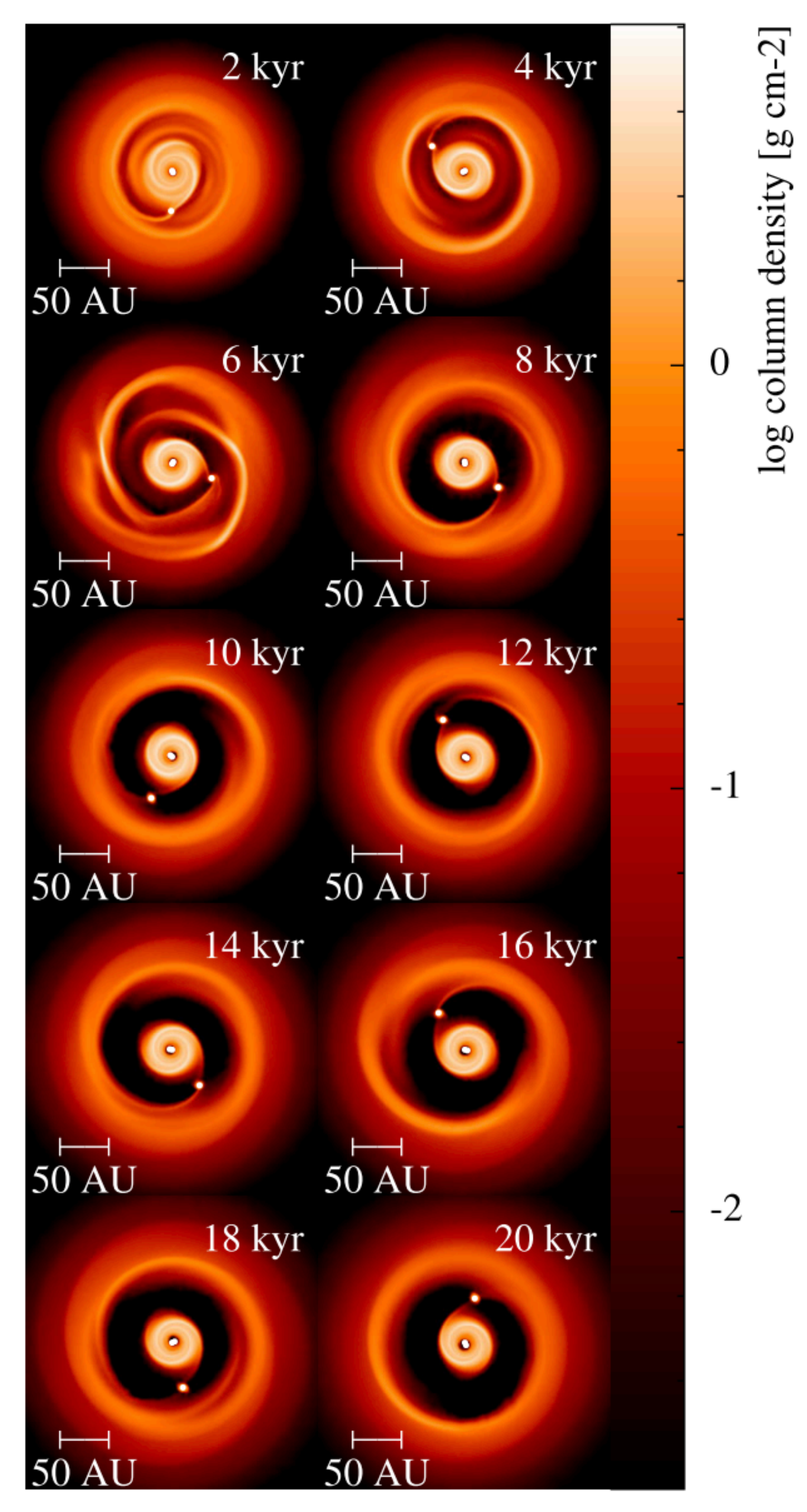
Figure 5 from Welsh & Orosz (2018)

CBP migration

Planet migration in massive circumbinary discs

Teasdale & Stamatellos, 2023
MNRAS 526, 6248–6257 (2023)

ABSTRACT
Most stars are in multiple systems, with the majority of those being binaries. A large number of planets have been confirmed in binary stars and, therefore, it is important to understand their formation and dynamical evolution. We perform simulations to investigate the migration of wide-orbit giant planets (semimajor axis 100 au) in massive circumbinary discs (mass $0.1\,M_{\odot}$) that are marginally gravitationally unstable, using the three-dimensional Smoothed Particle Hydrodynamic code SEREN. We vary the binary parameters to explore their effect on planet migration. We find that a planet in a massive circumbinary disc initially undergoes a period of rapid inward migration before switching to a slow outward migration, as it does in a circumstellar disc. However, the presence of the binary enhances planet migration and mass growth. We find that a high binary mass ratio (binary with equal mass stars) results in more enhanced outward planet migration. Additionally, larger binary separation and/or higher binary eccentricity results to a faster outward planet migration and stronger planet growth. We conclude that wide-orbit giant planets attain wider final orbits due to migration around binary stars than around single stars.



CBPs Big

…and small, maybe?

- Dilution of transit signals in binaries:
  - R_p, R_{CBP}: Planet or circumbinary planet radius
  - δ: transit depth
  - q: binary mass ratio $q = \frac{M_2}{M_1}$

$$R_p = R_{star}\sqrt{\delta}$$

$$R_{CBP} = R_{star}\sqrt{\delta(1 + q^{3.5})}$$

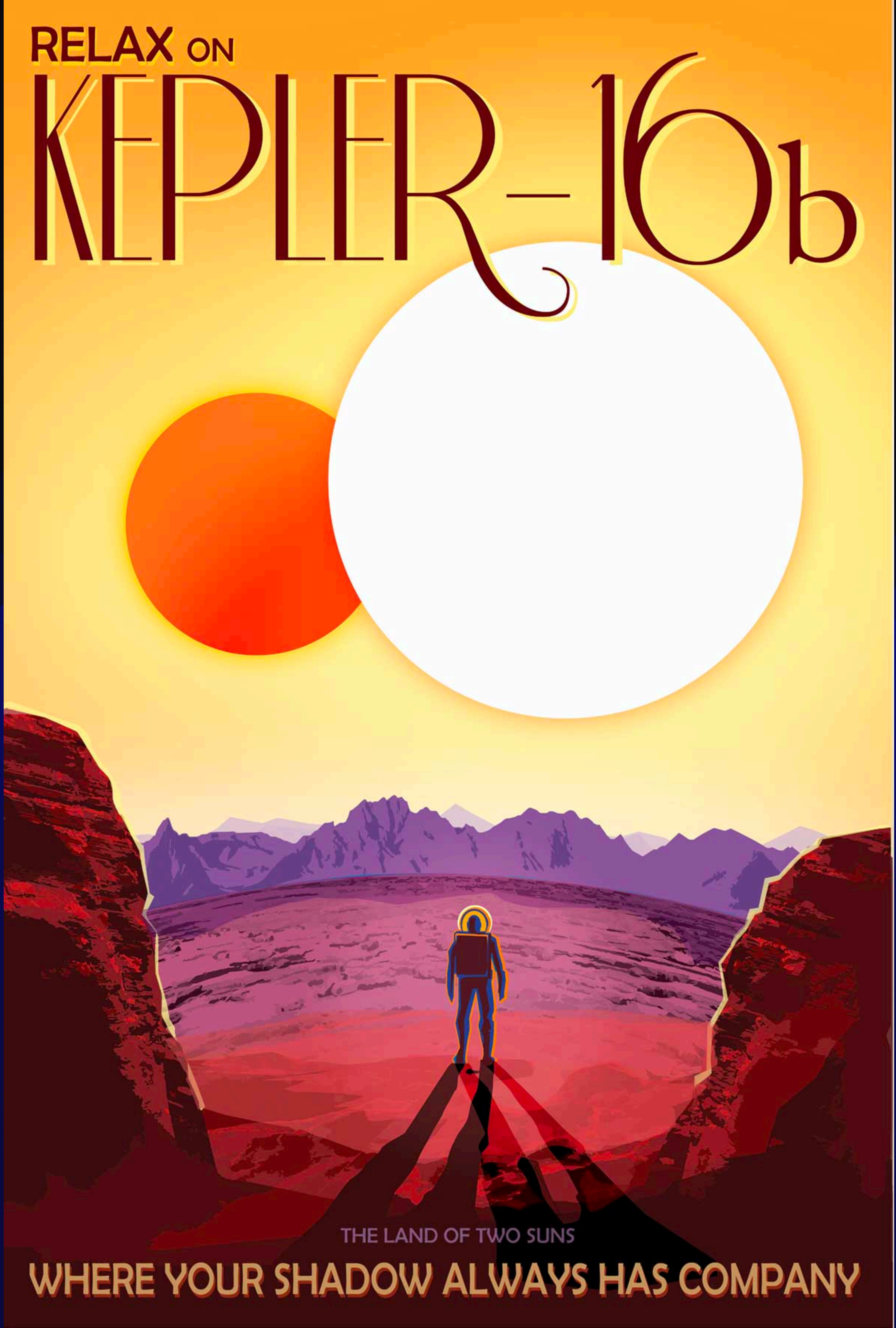
$$\frac{R_{CBP}}{R_p} = \sqrt{1 + q^{3.5}}$$

- Simulations of CBP formation in a coplanar disk show that these systems yield fewer and more massive planets than those with single star hosts (Childs & Martin, 2021)
- Stable formation of terrestrial planets is permitted (Barbosa et al., 2020)
- Low mass planets may be disrupted or ejected during migration through binary resonances
  - Especially for smaller rocky planets in the presence of a giant

The 1st transiting CBP

Kepler-16AB b

PLANET TYPE Gas Giant	DISCOVERY DATE 2011
MASS 0.333 Jupiters	PLANET RADIUS 0.754 x Jupiter
ORBITAL RADIUS 0.7048 AU	ORBITAL PERIOD 228.8 days
ECCENTRICITY 0.01	DETECTION METHOD Transit

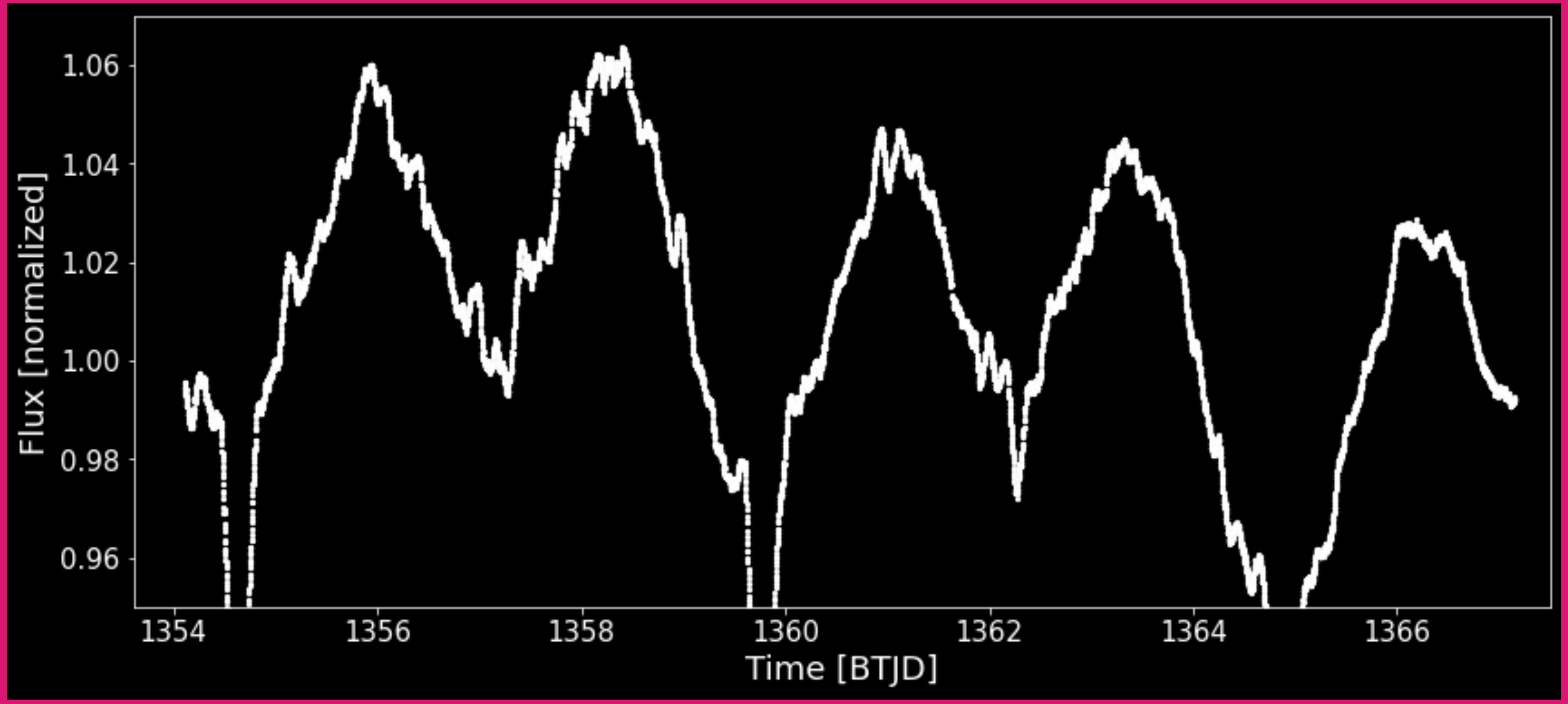


Finding transiting CBPs

...is quite the challenge

Binaries

✳Noisy/unruly EBs



✳Short baselines for most EBs

Planets

✳Transit timing, depth, and duration variability

- ✳Requires individual event searches

✳Dilution of transits

- ✳Difficult to find smaller planets!

$$\frac{R_{CBP}}{R_p} = \sqrt{1 + q^{3.5}}$$

What About Systems of CBPs?

Multiplicity in circumbinary systems

- ✳Two multi-planet systems discovered to date
  - ✳ Kepler-47: three planets
  - ✳ TOI-1338/BEBOP-1: two planets
- ✳Detections of additional transiting planets around known CBP hosts are expected to be limited, making probing this space difficult
- ✳We don't yet know whether most systems are single or multi-planet

TOI-1338/BEBOP-1

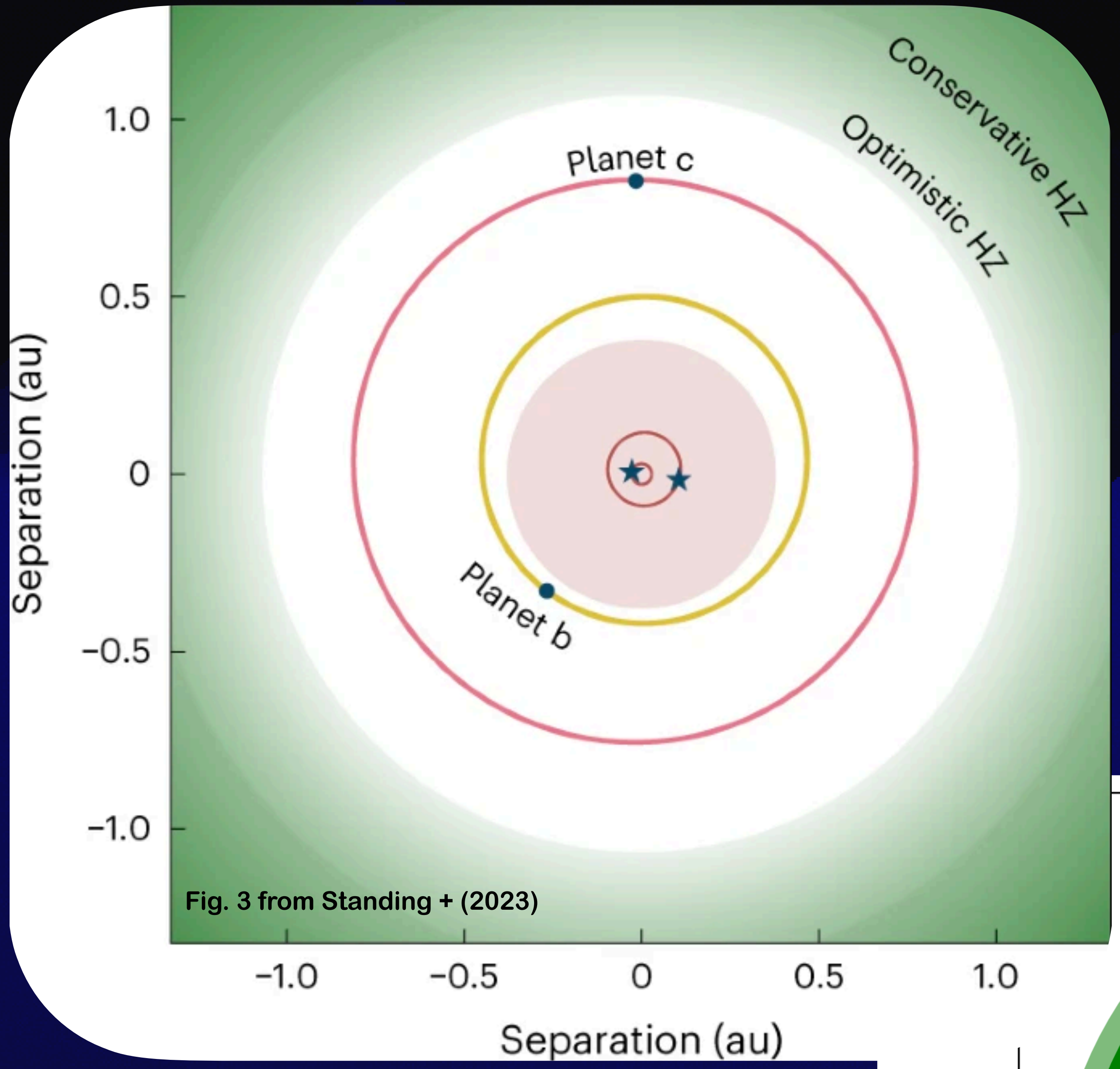


Fig. 3 from Standing + (2023)

Kepler-47

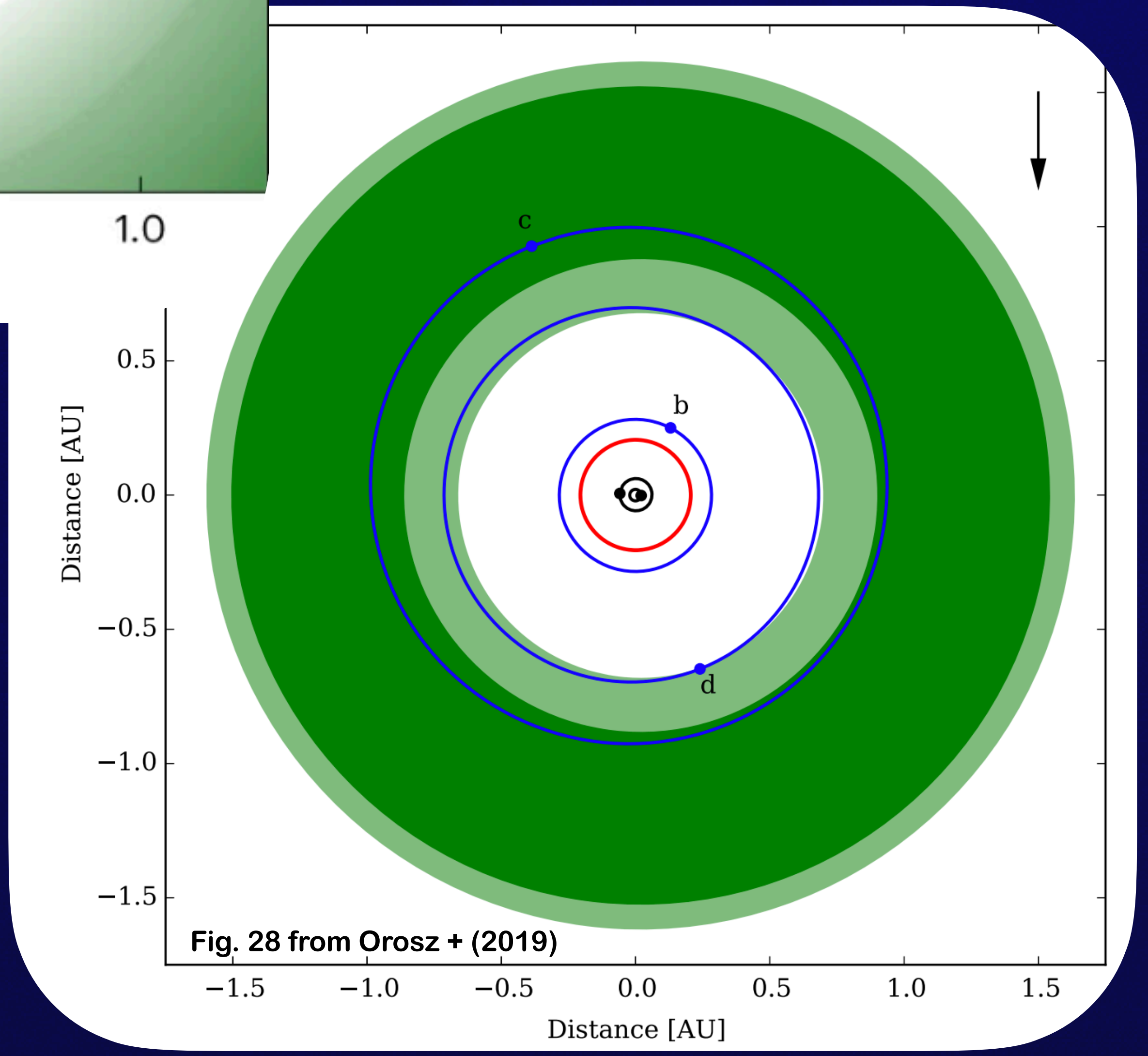
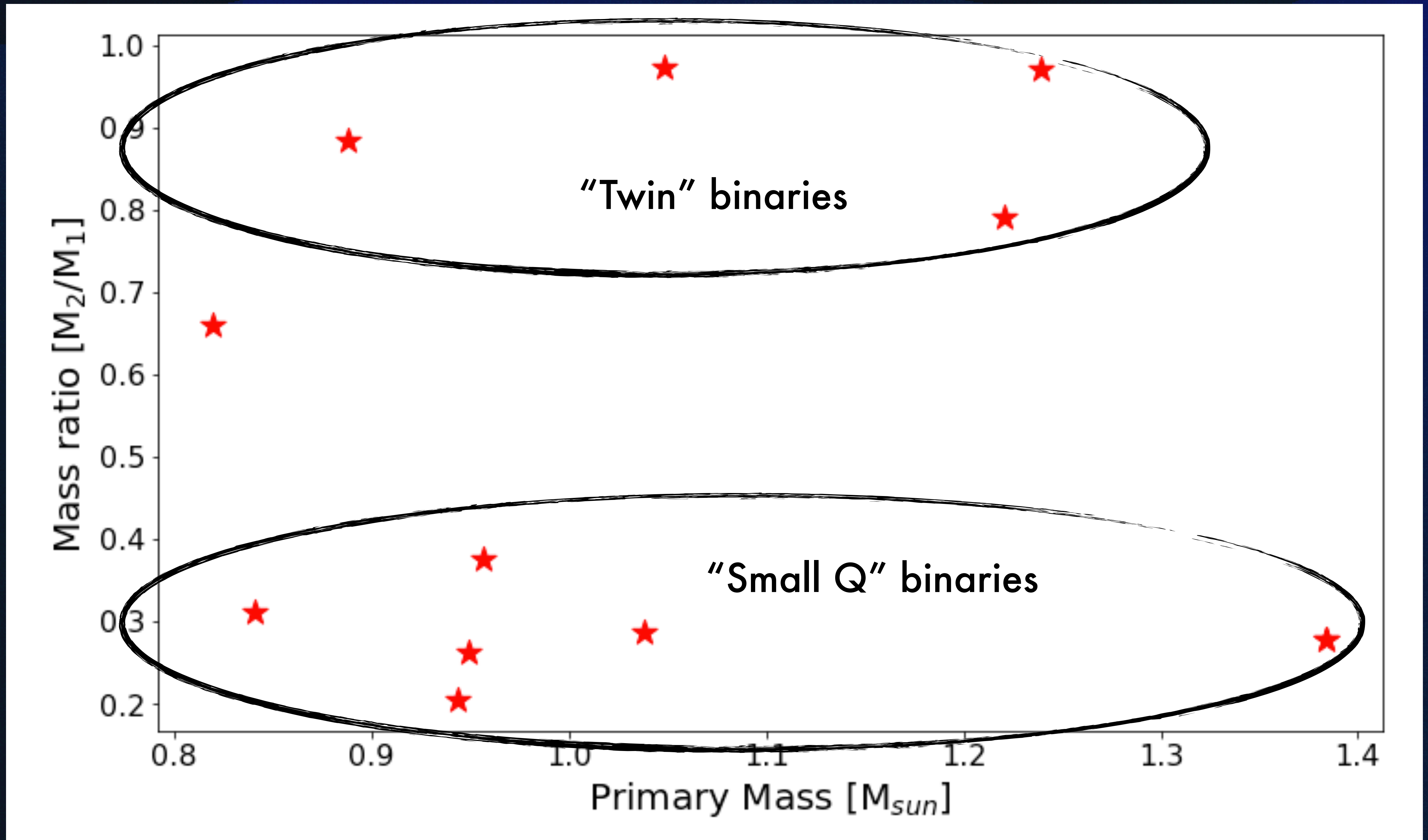


Fig. 28 from Orosz + (2019)

Known CBP Hosts

Further hints towards formation

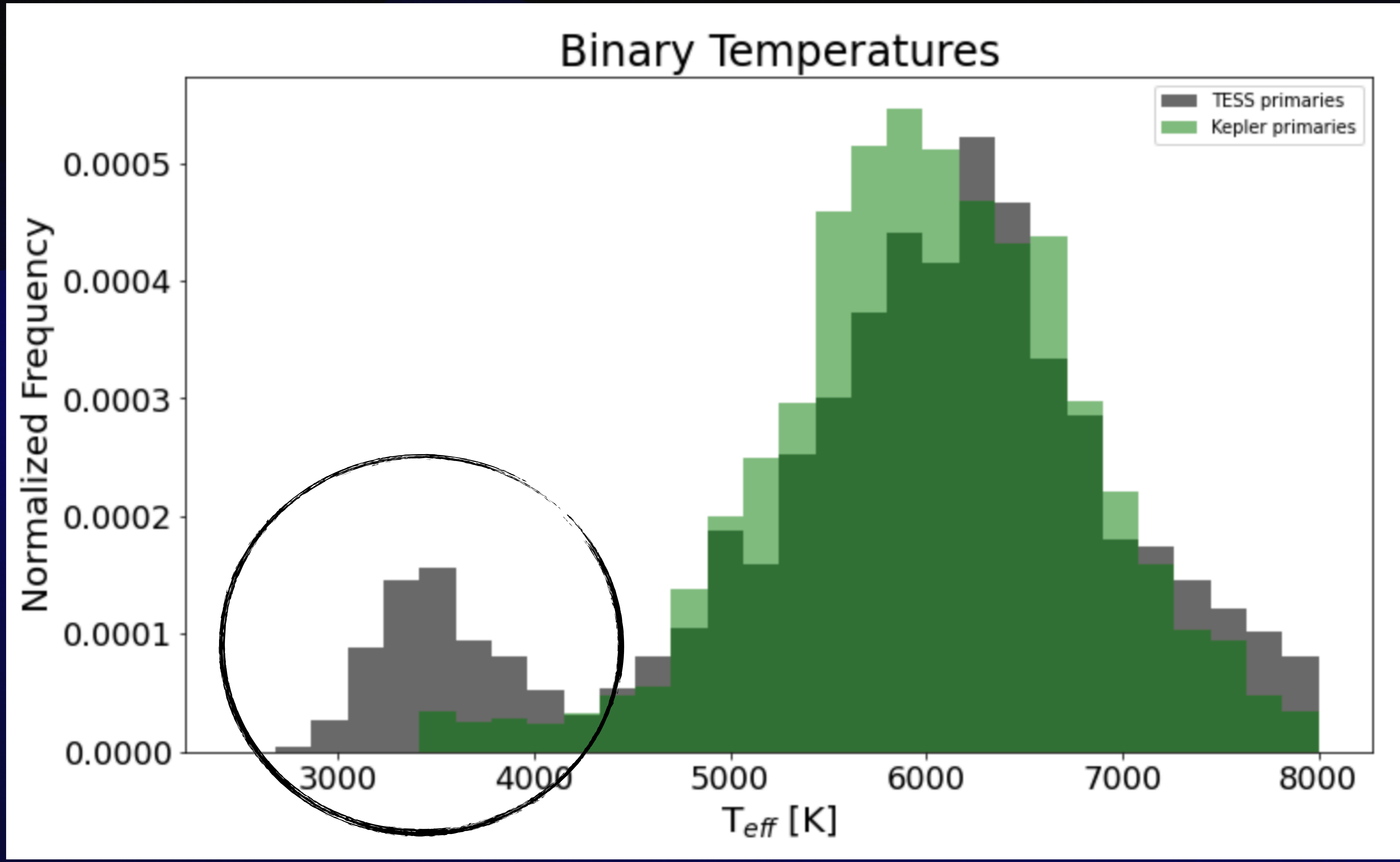
- Binary pairing is either "twin" binaries OR "small Q" binaries
  - Revealing of binary formation pathways!
-



CBP System	Primary Mass [M_{sun}]	Secondary Mass [M_{sun}]	Mass ratio $q = M_2/M_1$	Binary Period [d]
Kepler-16	1.384	0.386	0.279	41.08
Kepler-34	1.048	1.021	0.974	27.79
Kepler-35	0.888	0.786	0.885	20.73
Kepler-38	0.949	0.248	0.262	18.79
Kepler-47	0.957	0.342	0.375	7.45
Kepler-64*	1.384	0.386	0.279	20.00
Kepler-413	0.820	0.542	0.661	10.12
Kepler-453	0.944	0.195	0.206	27.32
Kepler-1647	1.221	0.968	0.792	11.26
Kepler-1661	0.841	0.262	0.311	28.16
TOI-1338	1.038	0.297	0.286	14.61
TIC172900988	1.239	1.203	0.971	19.65

Why no M+M CBPs (yet)?

- Low frequency of M+M binaries
  - No good formation channels for M dwarf primaries
- Previous observations and searches were not suited for M dwarfs
  - TESS gives us the opportunity to sample more M+M binaries!

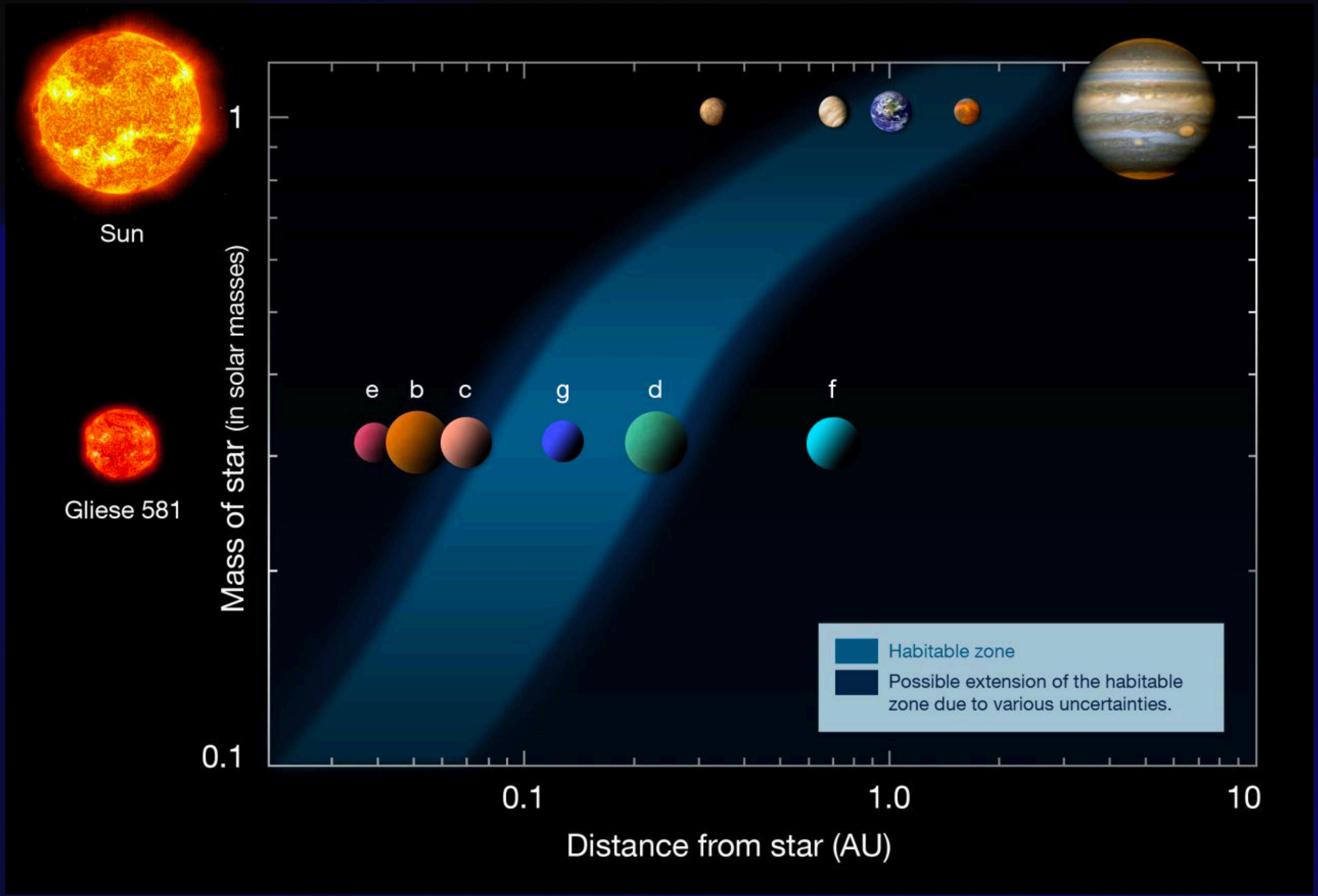


Plotted using data from D. J. Armstrong, et al. A catalogue of temperatures for Kepler eclipsing binary stars, *MNRAS* (2014)

Can M+M binaries yield planets?

Why are M+M binaries exciting?

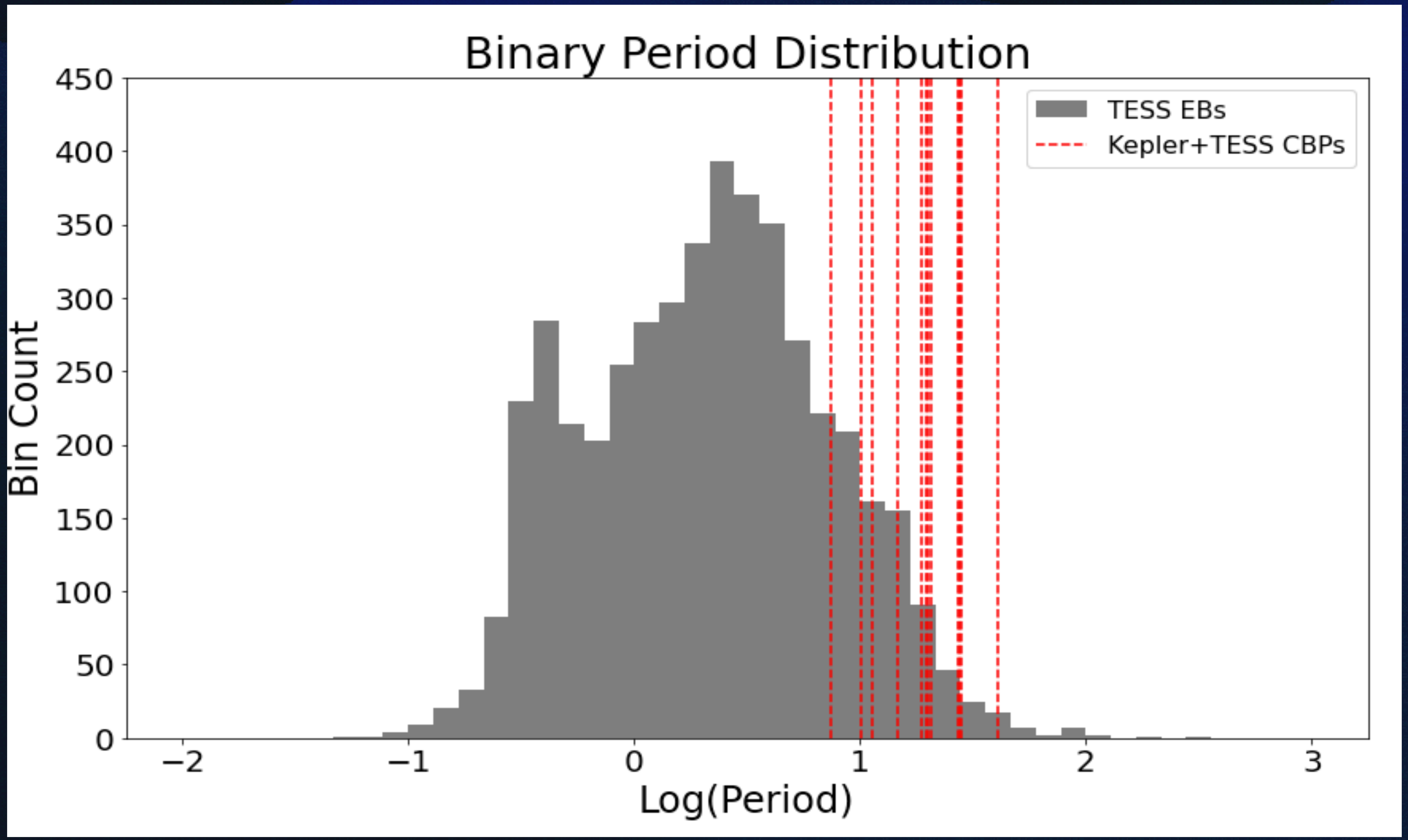
- Single M dwarfs are interesting for many reasons:
  - Hosts to diverse systems of planets
  - Challenging tests of planet formation (low- and high-mass alike)
  - More easily accessible HZ planets
- More M+M binaries are accessible than ever with TESS!
  - Represents a new chance to examine these questions from a different perspective



Known CBP Hosts

Further hints towards formation

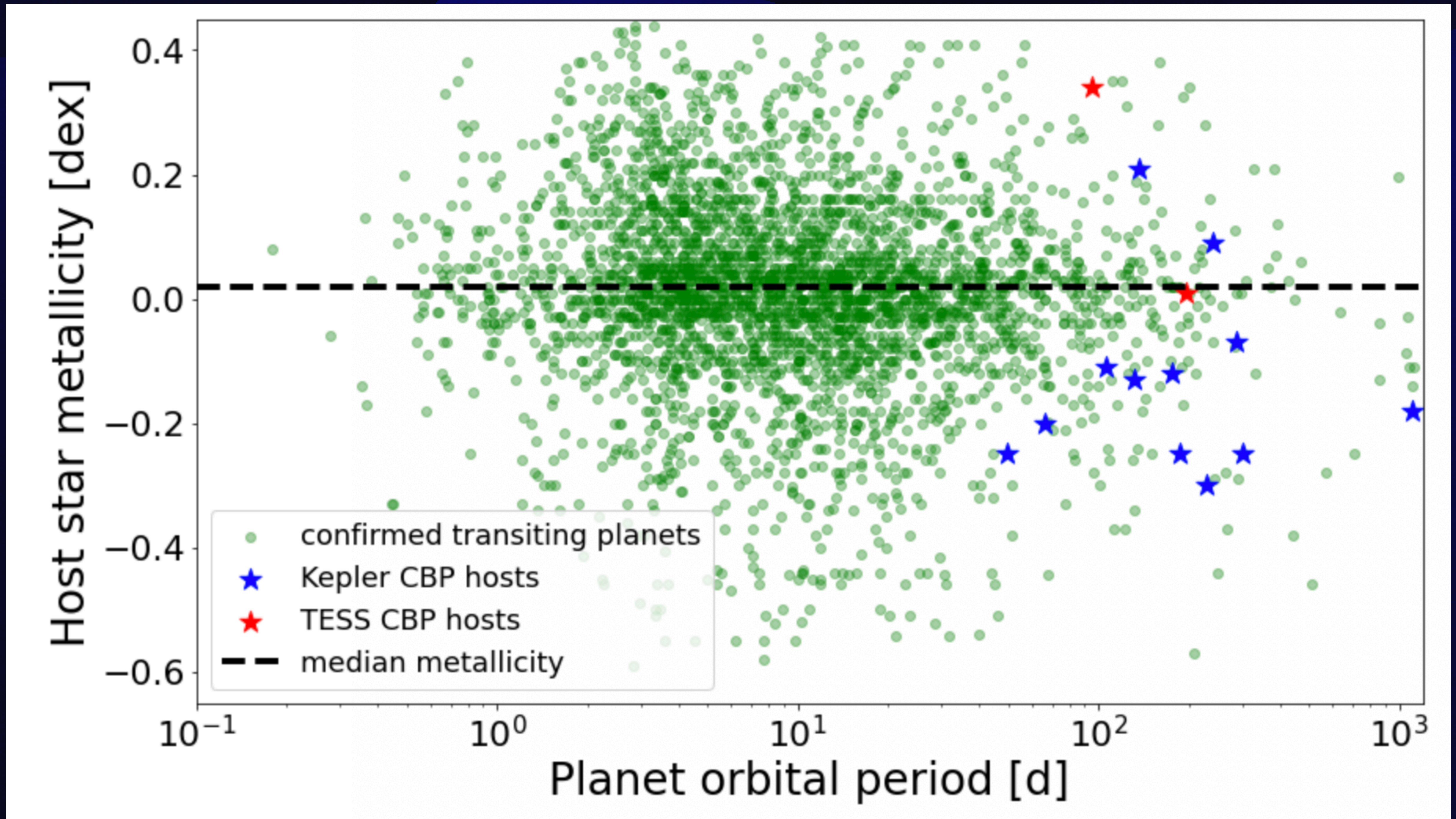
- Binary periods between roughly 7-50 days
- Why not shorter-period binaries? ← KLOTF!

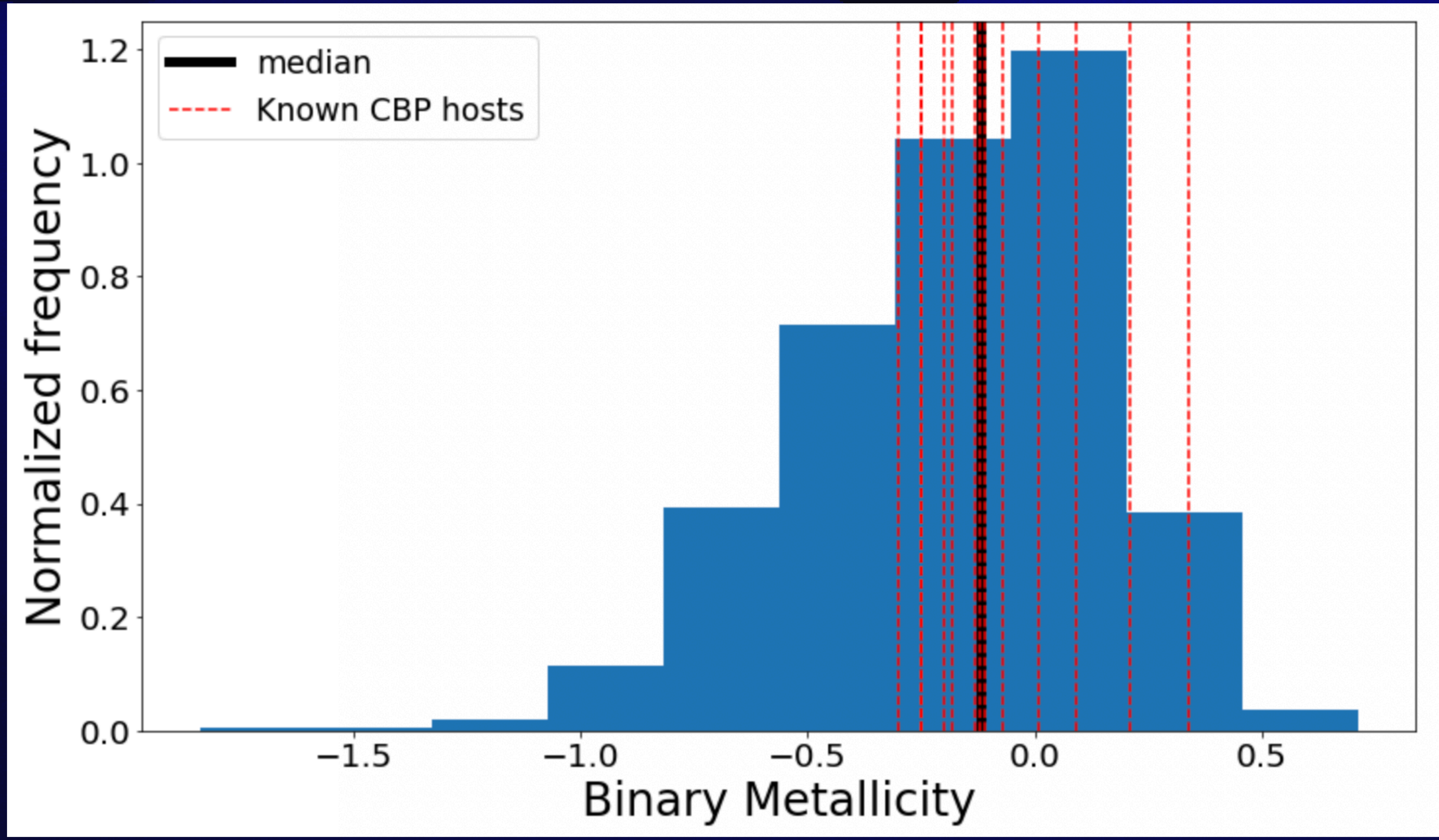


CBP System	Primary Mass [M_{sun}]	Secondary Mass [M_{sun}]	Mass ratio $q = M_2/M_1$	Binary Period [d]
Kepler-16	1.384	0.386	0.279	41.08
Kepler-34	1.048	1.021	0.974	27.79
Kepler-35	0.888	0.786	0.885	20.73
Kepler-38	0.949	0.248	0.262	18.79
Kepler-47	0.957	0.342	0.375	7.45
Kepler-64*	1.384	0.386	0.279	20.00
Kepler-413	0.820	0.542	0.661	10.12
Kepler-453	0.944	0.195	0.206	27.32
Kepler-1647	1.221	0.968	0.792	11.26
Kepler-1661	0.841	0.262	0.311	28.16
TOI-1338	1.038	0.297	0.286	14.61
TIC172900988	1.239	1.203	0.971	19.65

Clues from host metallicity

- Metallicity loosely tells us about the resources available for planet formation
- Majority of CBP hosts are sub-solar metallicity and below median of transiting planet hosts
- What about compared to other binaries?
  - Further clues to tight binary formation!





How do we look for more?

TESS Eclipsing Binary Sample

~4,500 in 2-min PM sample + ~500,000 in FFI sample

Acknowledgement to Andrej Prša and his team of collaborators for the 2-min EB sample and their continuing work on the forthcoming FFI sample.

Acknowledgement to Ethan Kruse and Brian Powell for their willingness to share their list of FFI EBs prior to publication!

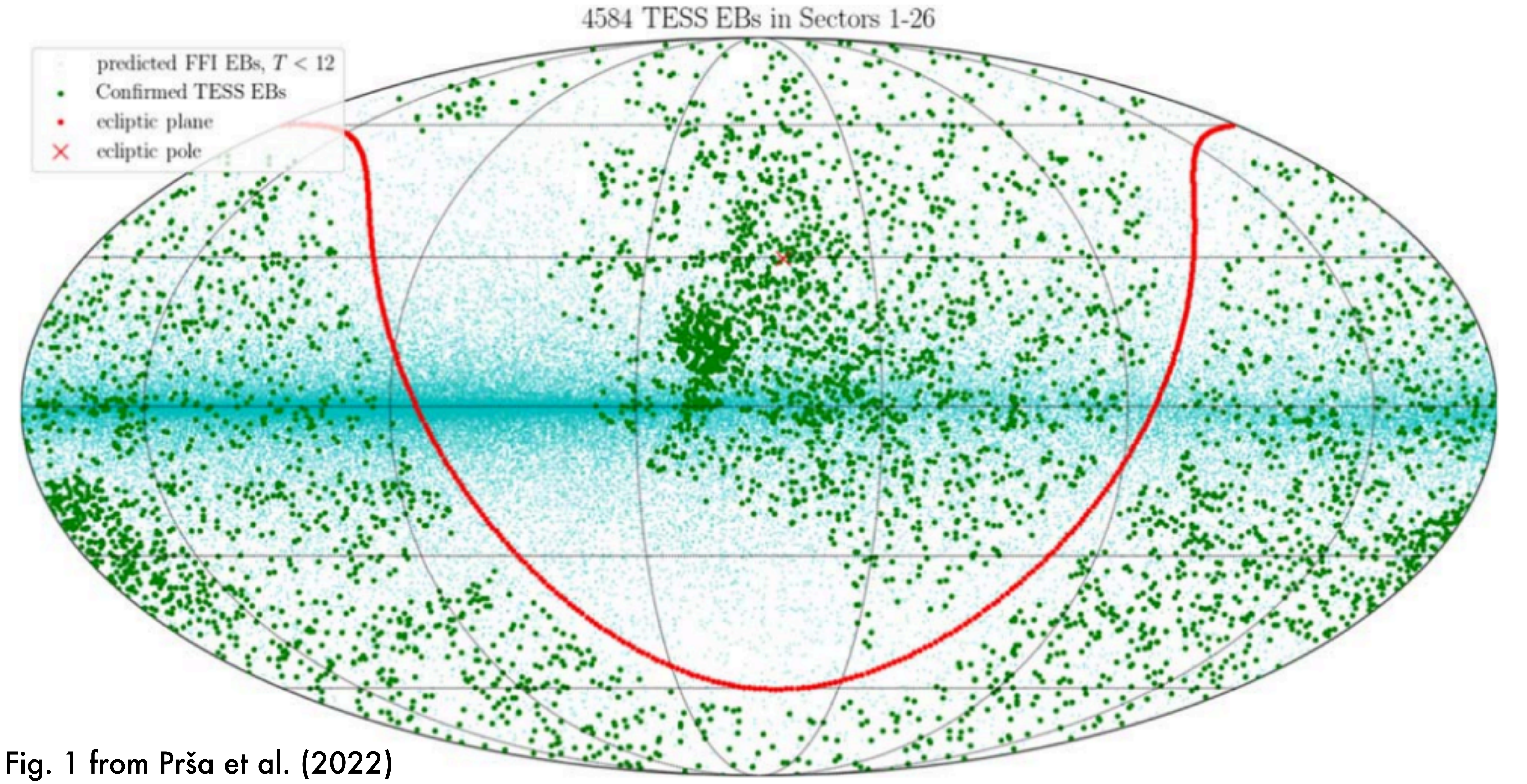
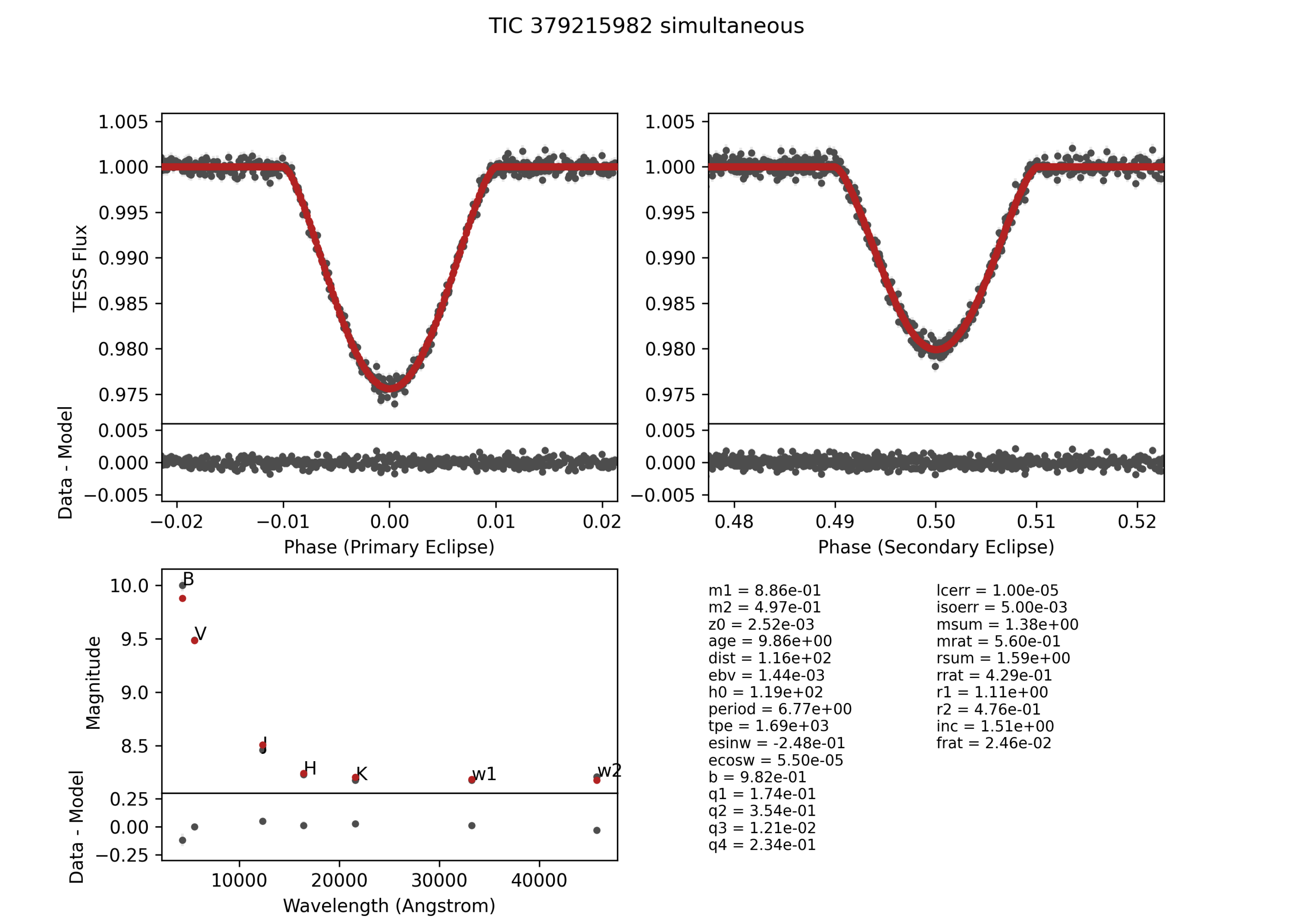


Fig. 1 from Prša et al. (2022)

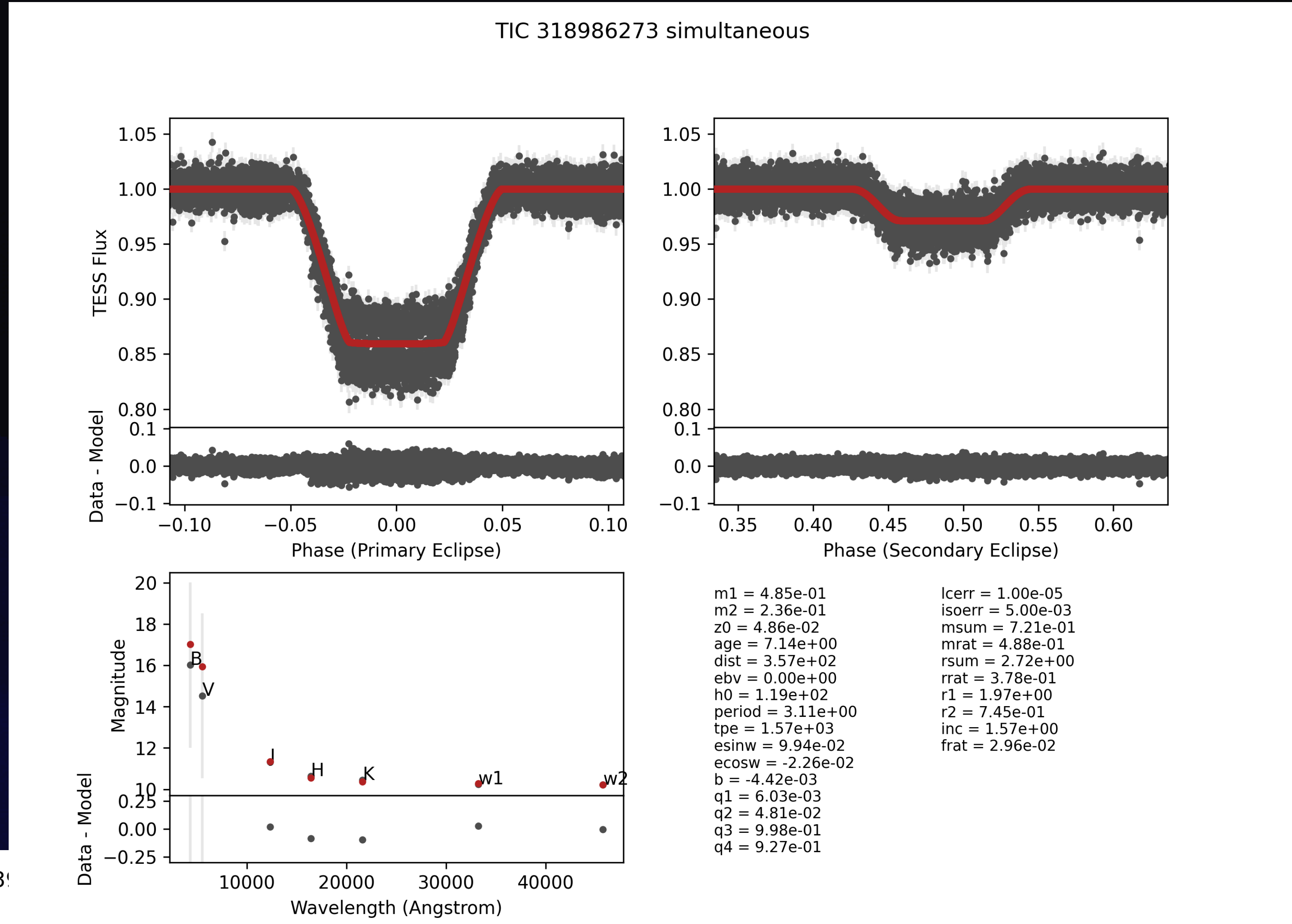
Know thy Binary

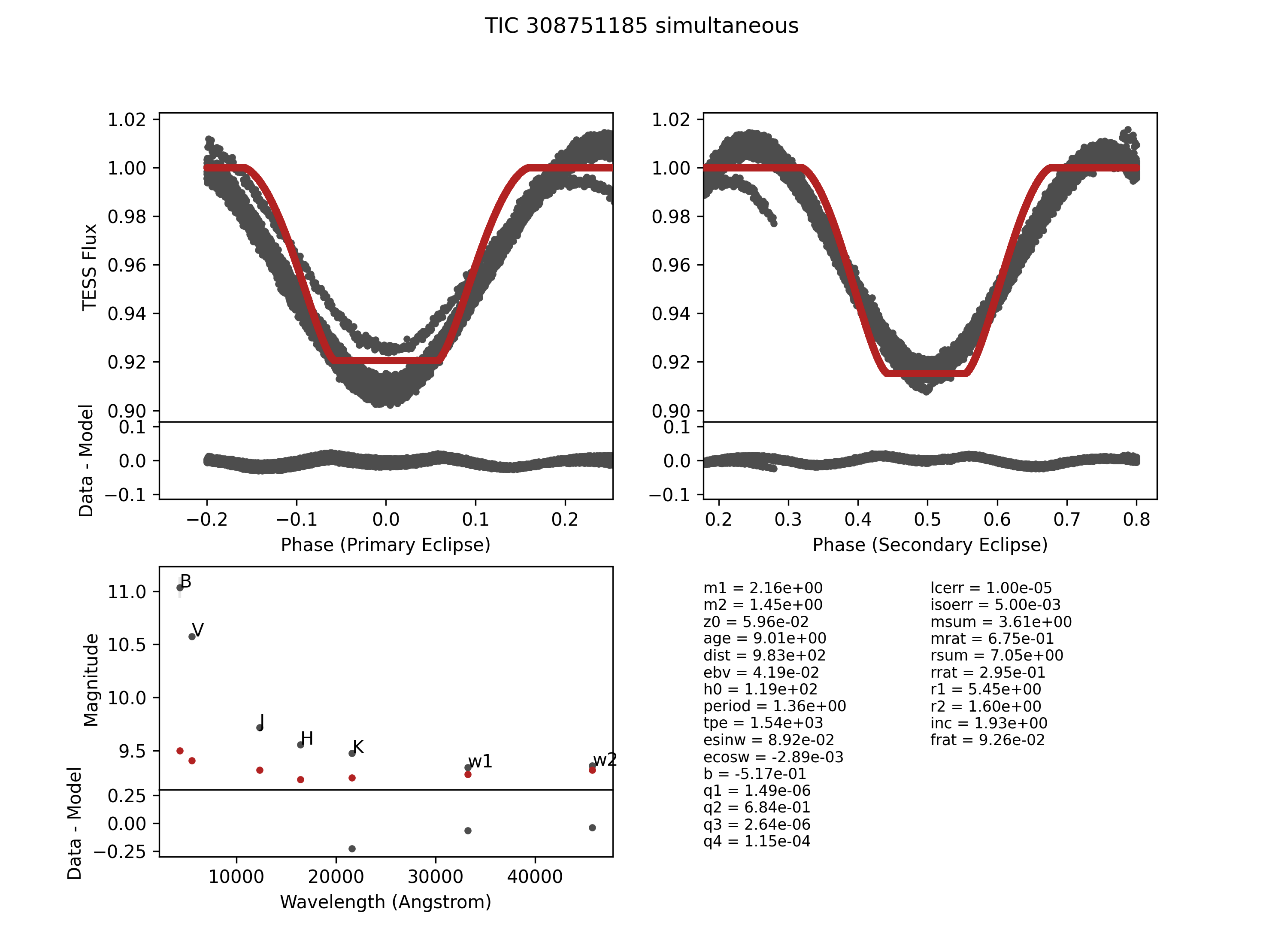
To know thy planet

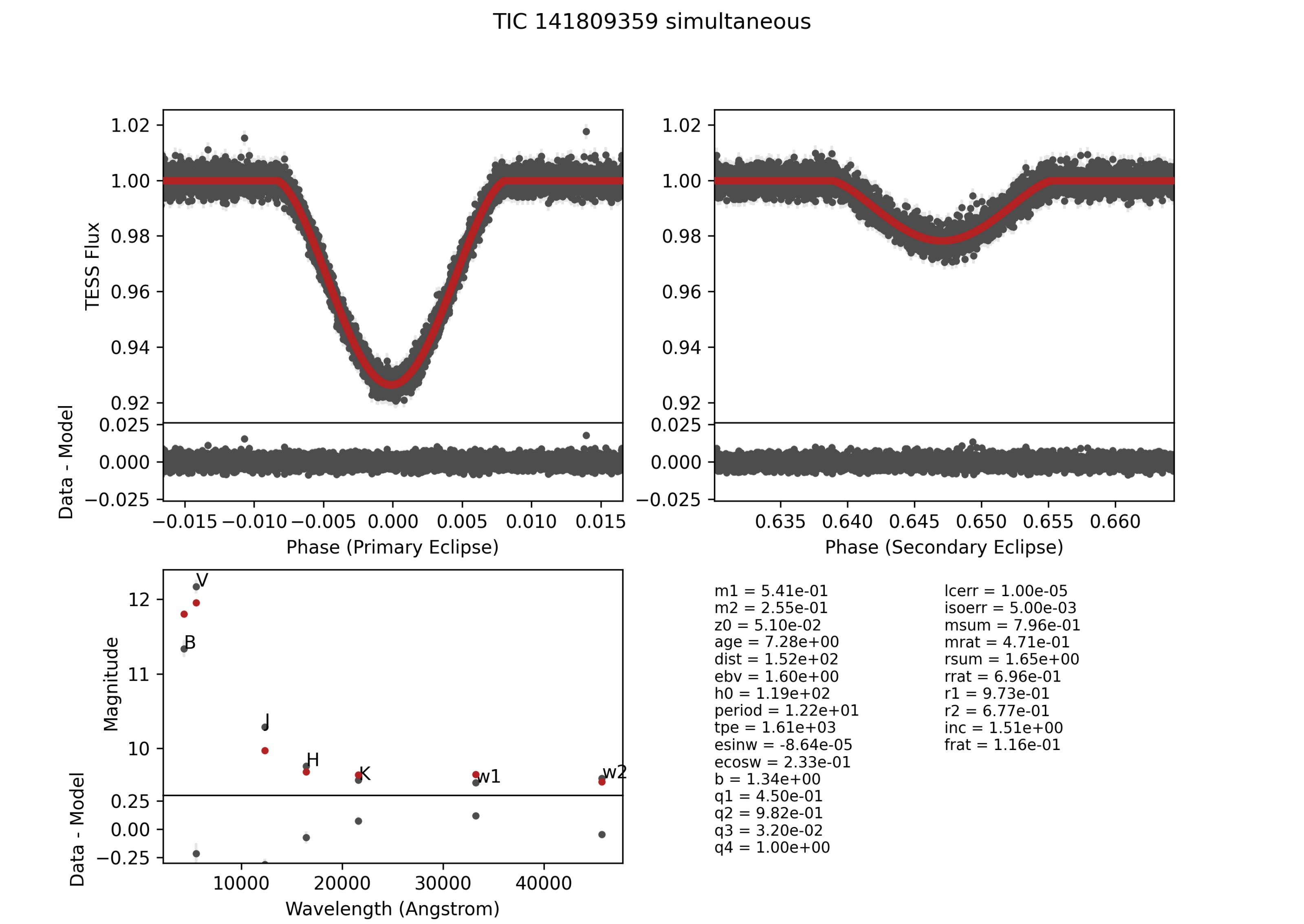


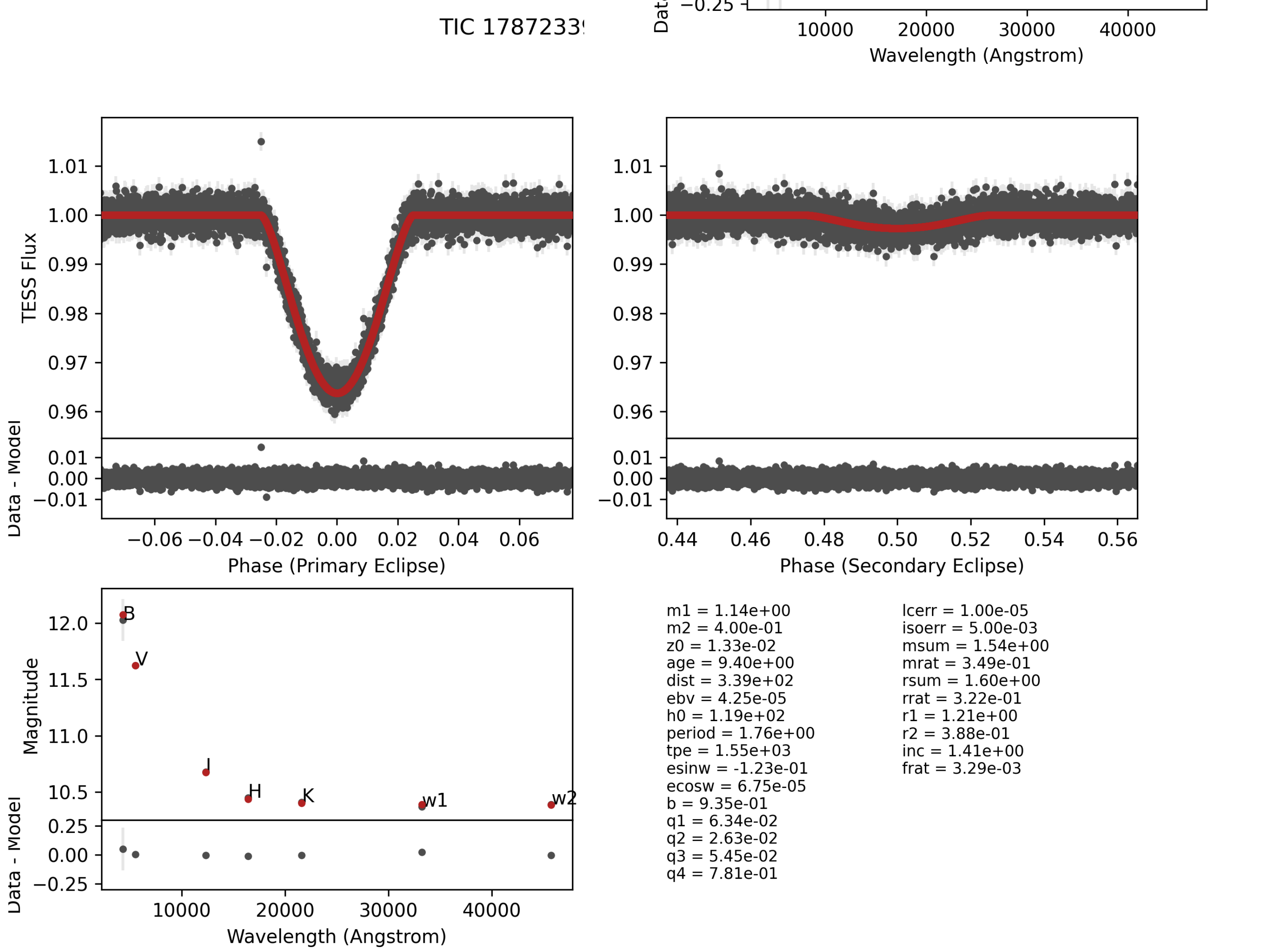
Knowing the physical characteristics of the stars in the binary will in turn allow us to calculate physical parameters for the planets we find

But how??

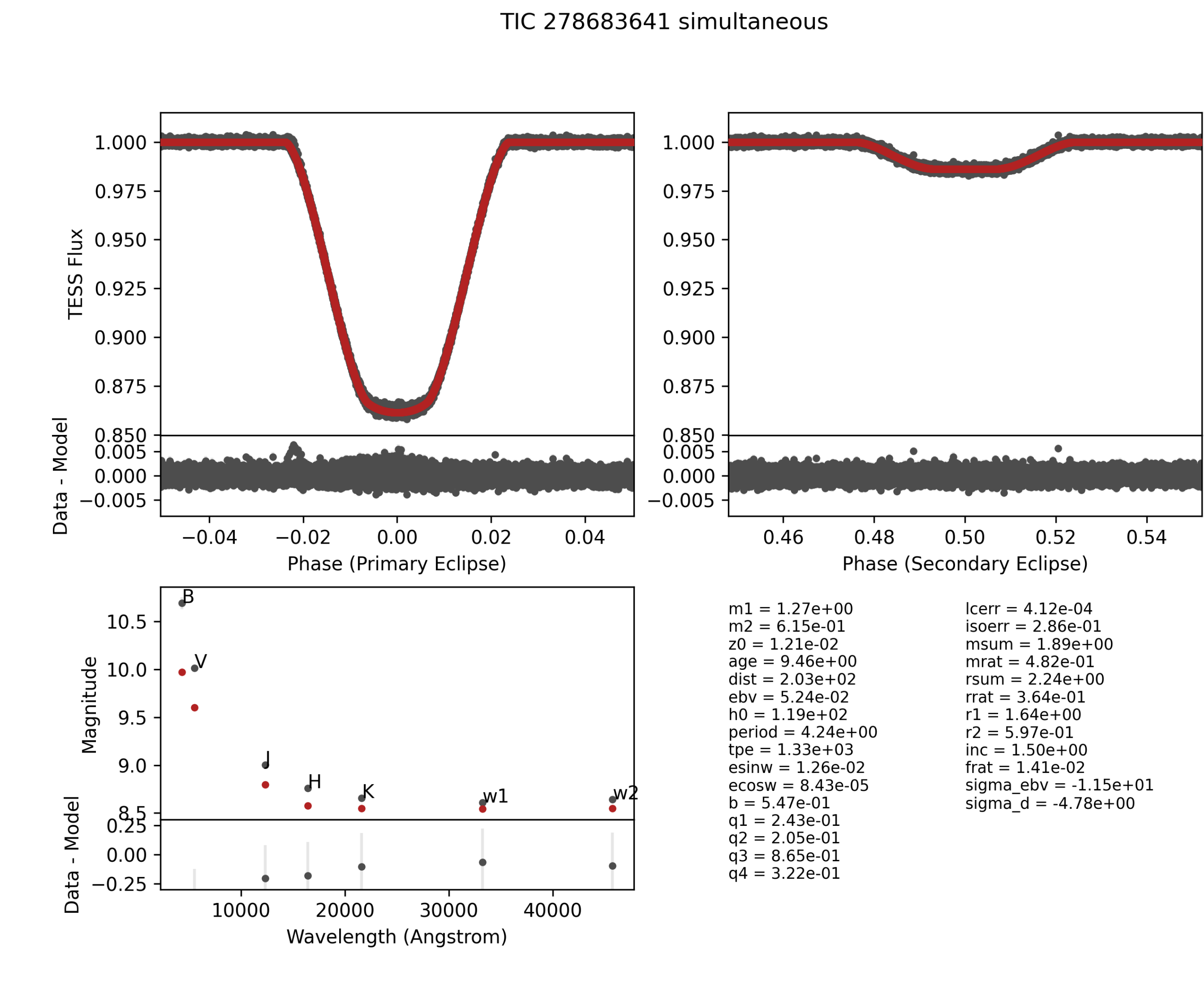




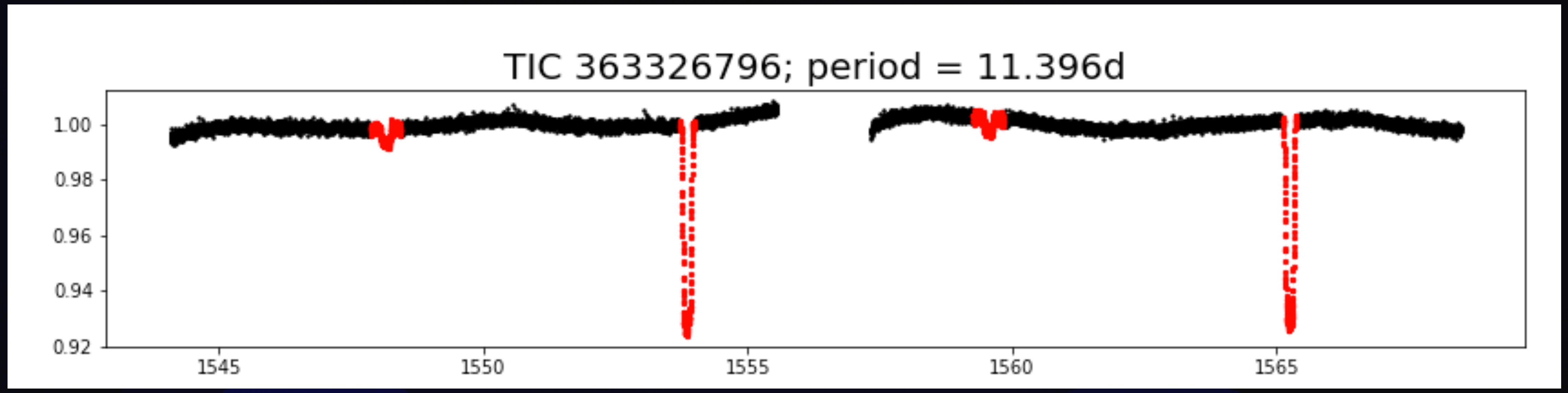


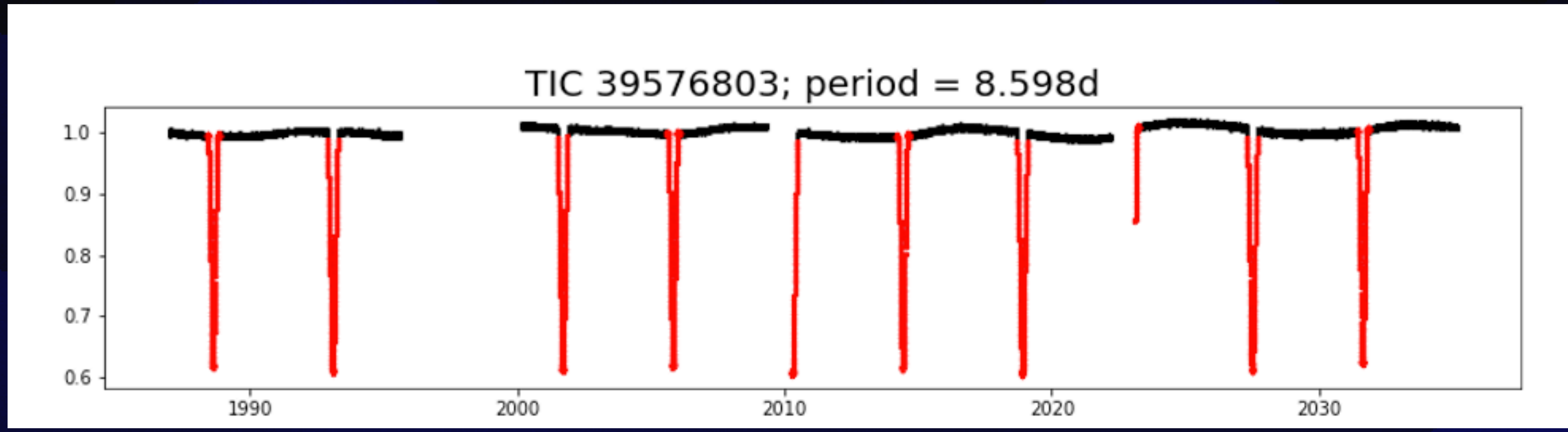


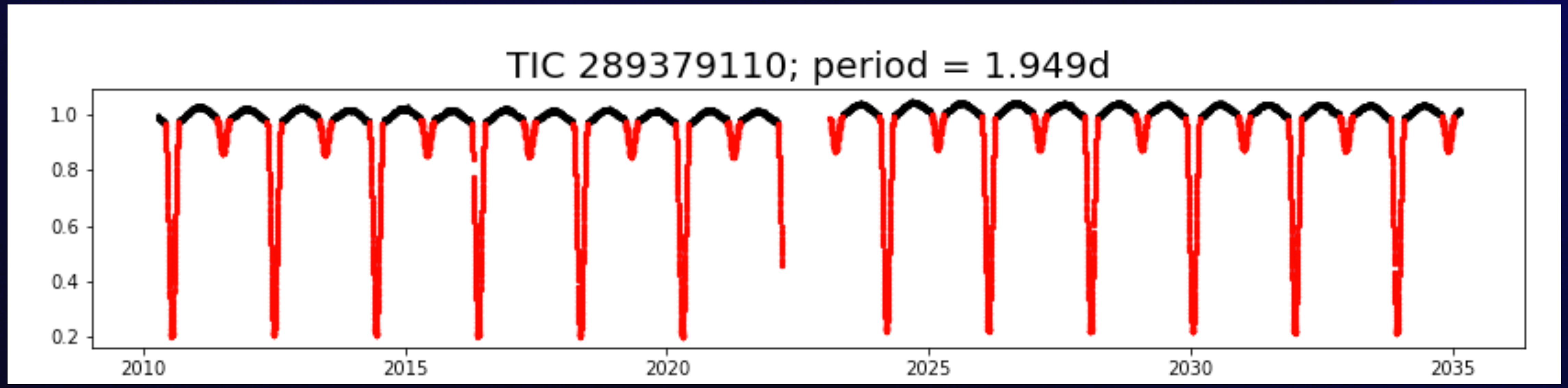
By using information about the binaries we get "for free" from light curves and fitting this in tandem with flux information in different bandpasses, we can extract physical parameters like mass and radius

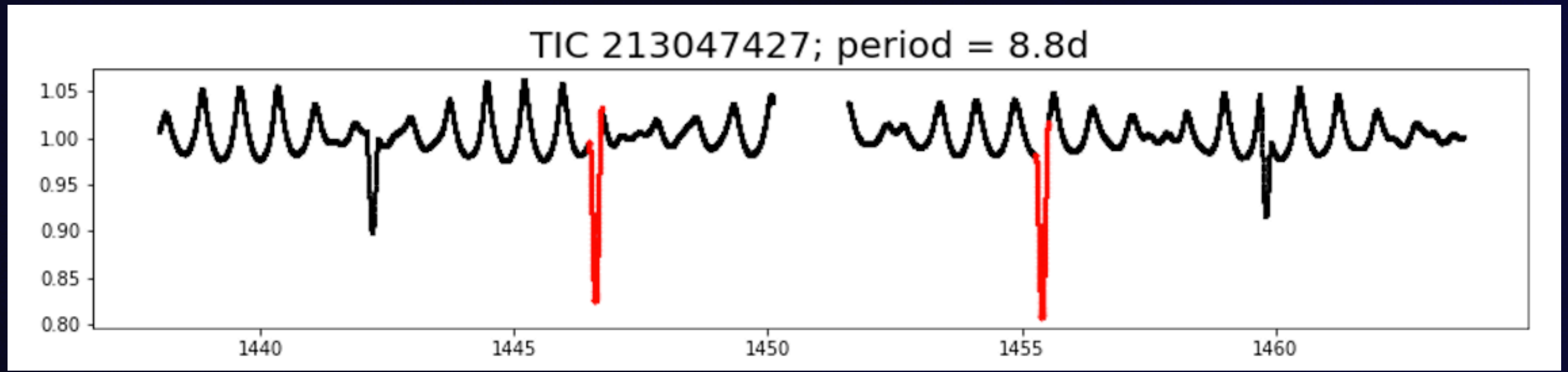


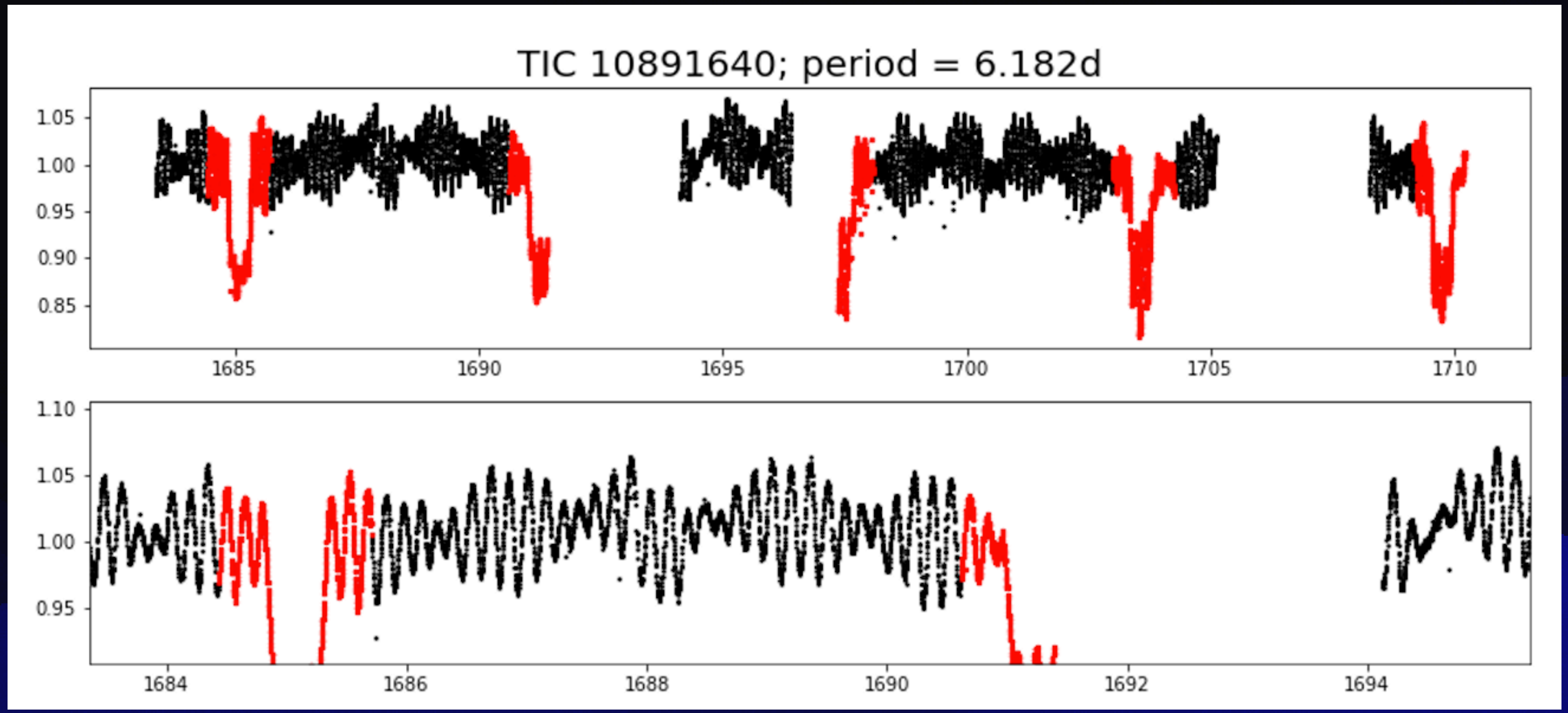
Light curve examples

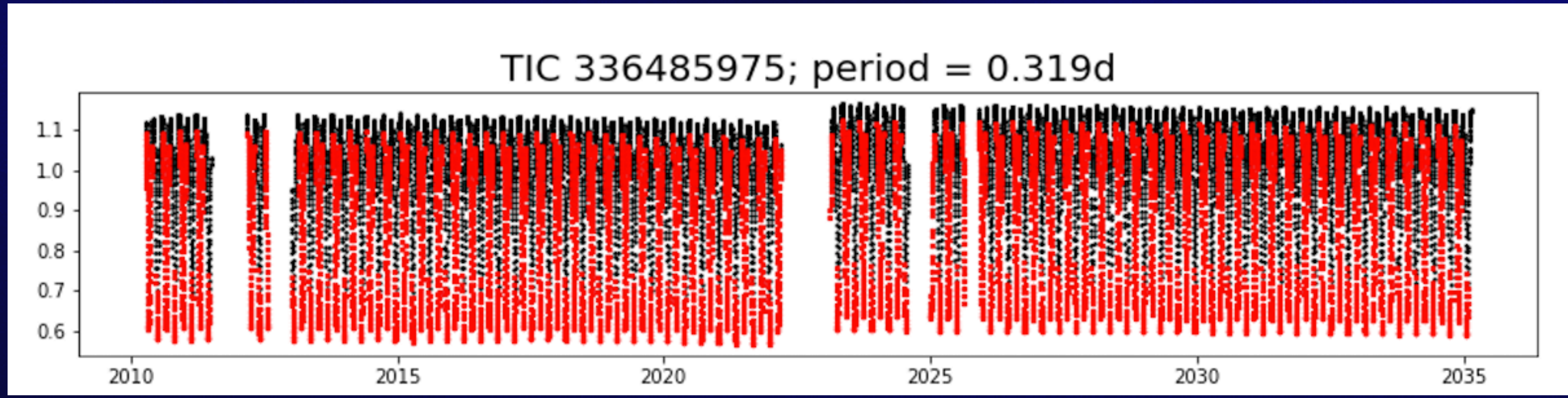


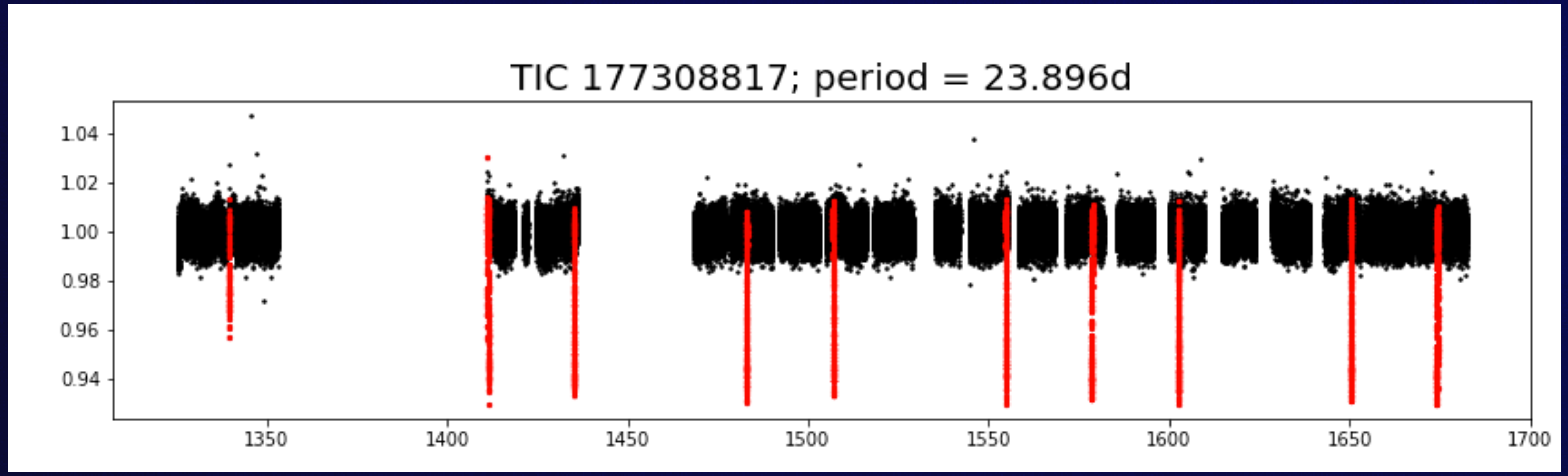






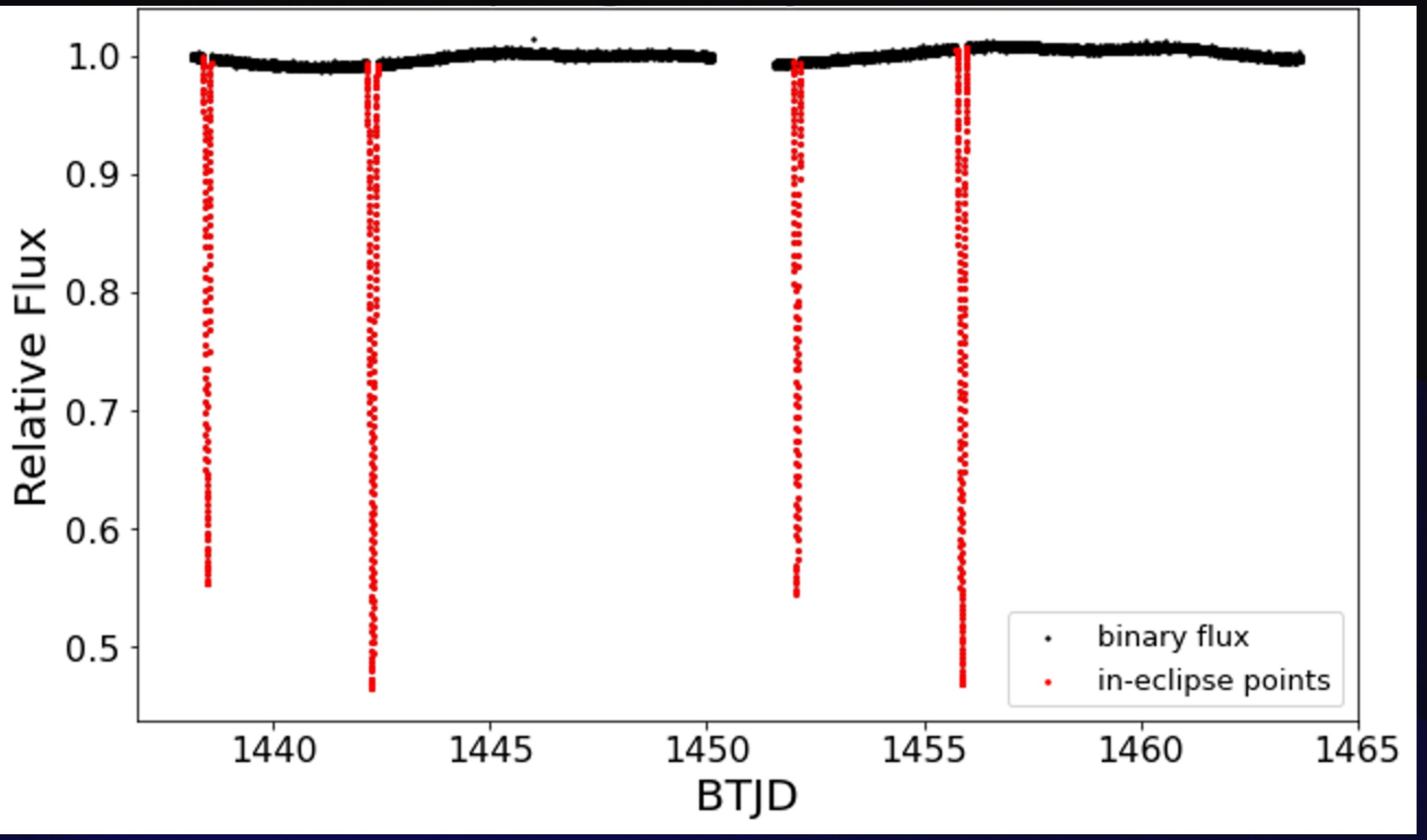




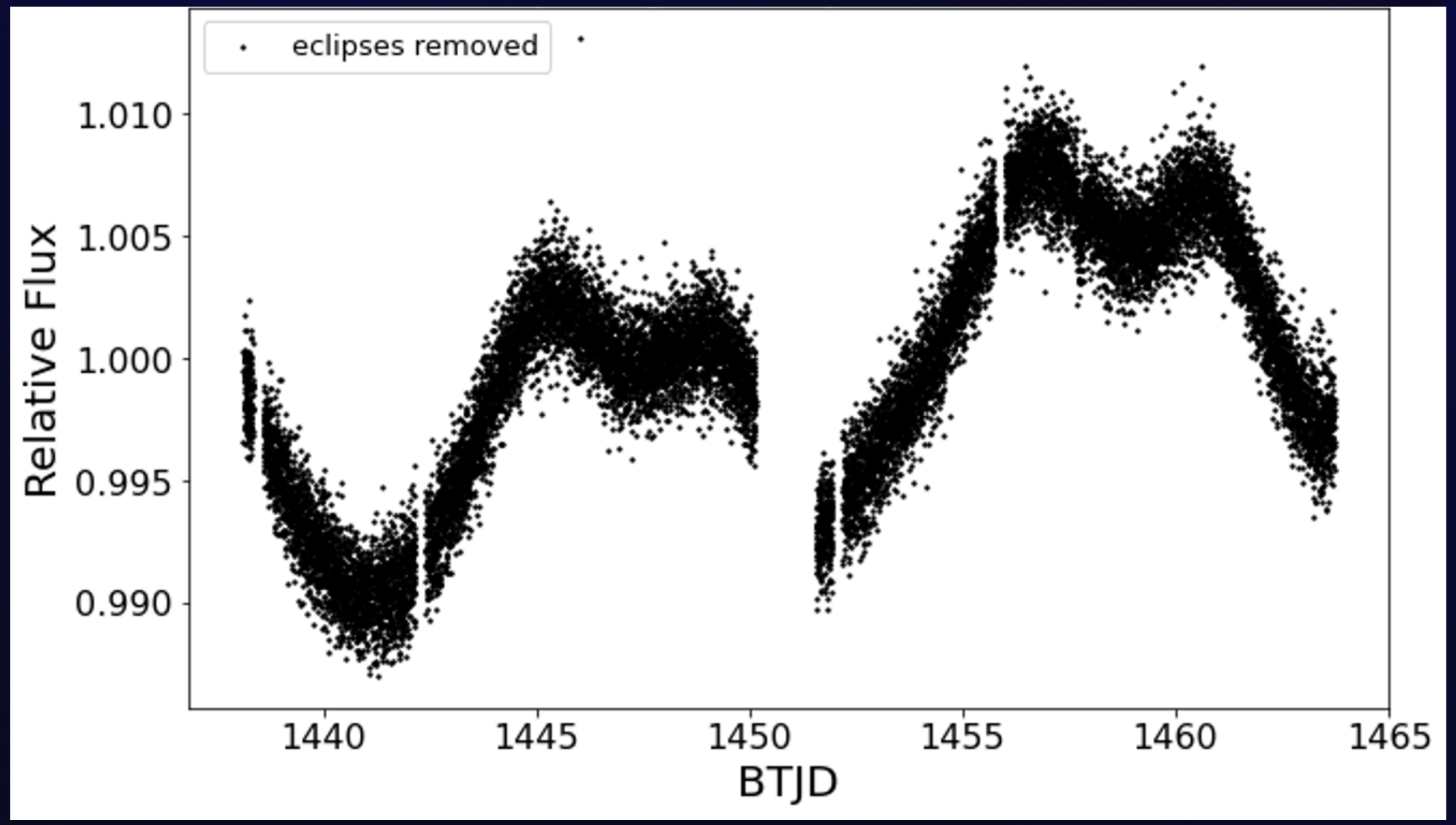


The Search for Transit Events

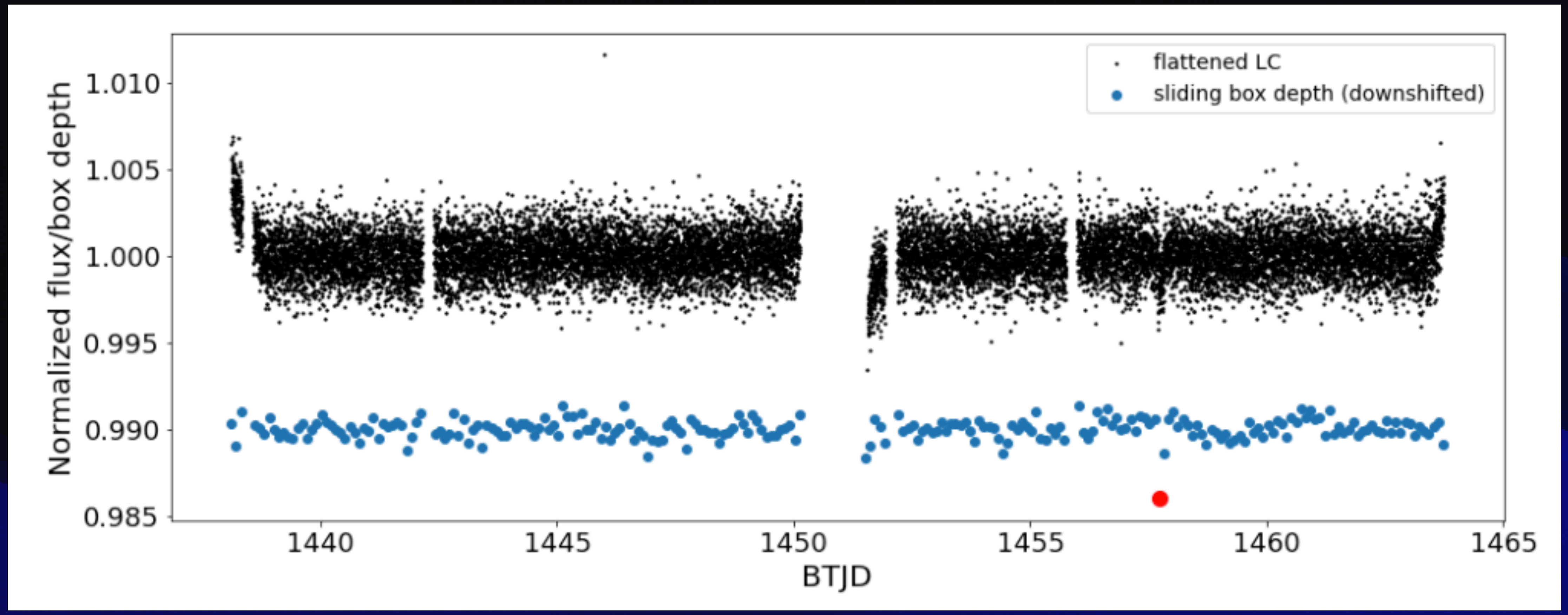
Stage 1: Generate light curves



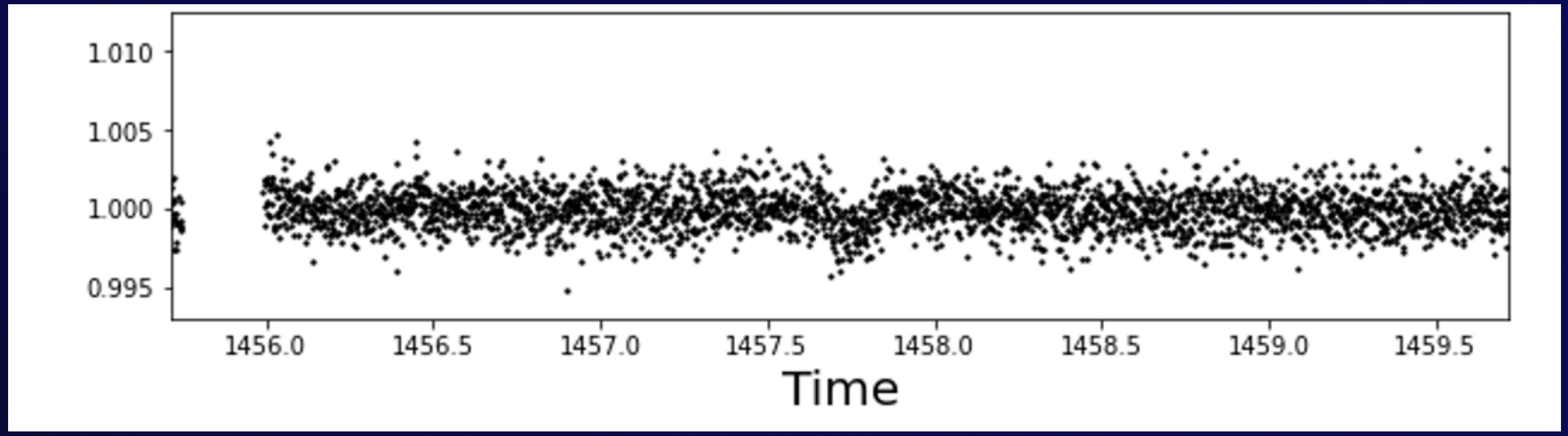
Stage 2: Identify and remove eclipses



Stage 3: Search for events



Stage 4: Voilà!



Example Calculation: Smallest detectable CBP

up&up

Calculating the min detectable planet for ~~an~~ our M+M sample of binaries

$$SNR = \frac{\delta \; D}{\sigma_{ooe}(T_{mag})} \sqrt{N_{pts}}$$

↖ comes from J's paper

assume $D = 1$

assume we know N_{pts}

$SNR = 10$

$$\frac{SNR \cdot \sigma(T_{mag})}{D\sqrt{N_{pts}}} = \delta \quad .1$$

$$\frac{1 R_J}{.5 R_*} \quad .2$$

$N_{pts} = dur \cdot 48$ for 30 min cadence [days]

$$\delta = \left(\frac{F_*}{F_{tot}}\right)\left(\frac{R_p}{R_*}\right)^2 =$$

↑ ½ for equal mass

~~.0012~~

0.05 .02

$$\frac{SNR \cdot \sigma(T_{mag})}{D\sqrt{dur \cdot 48}} = \frac{1}{2}\left(\frac{R_p}{R_*}\right)^2$$

.003

~~.0~~

.008

$$\boxed{R_* \sqrt{\frac{2 \cdot SNR \cdot \sigma(T_{mag})}{D\sqrt{dur \cdot 48}}} = R_p}$$

or $L = 4\pi R^2 \sigma_{SB} T^4$

- how to find R_*?

in the TIC:

$$\log\left(\frac{R}{R_\odot}\right) = \frac{1}{5}\left[4.74 - 5 + 5\log D - G - 10\log\left(\frac{T_{eff}}{5772}\right) - BC\right]$$

D ← dist

G ← gaia mag

BC ← bolometric correction

Could we find Tatooine?

Exercise: Circumbinary Planet Habitability

CBP habitability

stability

$a_{crit} = a_{bin}[A + B\cancel{e_{bin}} + C\mu_{bin} + \cancel{D\mu e} + E\mu^2 + \cancel{F e^2} + \cancel{G e^2\mu^2}]$

$a_{bin} = .1$, $e_{bin} = 0$ A = 1.6 E = -5.09

$\mu = \frac{m_2}{m_1+m_2} = .5$ C = 4.12

$a_{crit} = .1[1.6 + (4.12 \cdot .5) + (-5.09 \cdot .5^2)]$

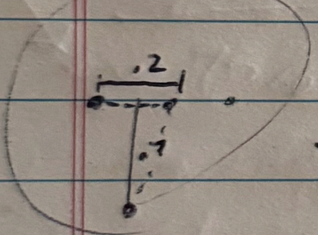
2.06 1.27

$a_{crit} = 2.39\ a_{bin}$

What the min and max temperatures of this configuration?

* planet has albedo of .3

* $T_{eff_1} = T_{eff_2} = 5000k$, $R_{s_1} = R_{s_2} = 0.004\ AU$



$T_{eq}^4 = \frac{F_s(1-A_B)}{4\sigma\epsilon}$ $F_{s,tot} = \frac{L_s}{4\pi r_{s_1}^2} + \frac{L_s}{4\pi r_{s_2}^2}$

$L_s = \sigma T_{eff}^4 4\pi R_s^2$ $F_s = \frac{\sigma T_{eff}^4 4\pi R_s^2}{4\pi r_{s_1}^2} + \frac{\sigma T_{eff}^4 4\pi R_s^2}{4\pi r_{s_2}^2}$

$T_{eq}^4 = $ L

$F_s = \sigma T_{eff}^4 R_s^2 \left(\frac{1}{r_{s_1}^2} + \frac{1}{r_{s_2}^2}\right)$

$c = \sqrt{.1^2 + .7^2}$ $r_{s_1} = r_{s_2} = \frac{\sqrt{2}}{2}$

.01 + .49

$c = \sqrt{1/2} = \frac{\sqrt{2}}{2}$

$F_s = 4\sigma T_{eff} R_s^2$ or

or

$F_s = (4.34\sigma T_{eff} R_s^2)$

$r_{s_1} = .6$, $r_{s_2} = .8$ → 1.5625 + 2.77

= 4.34

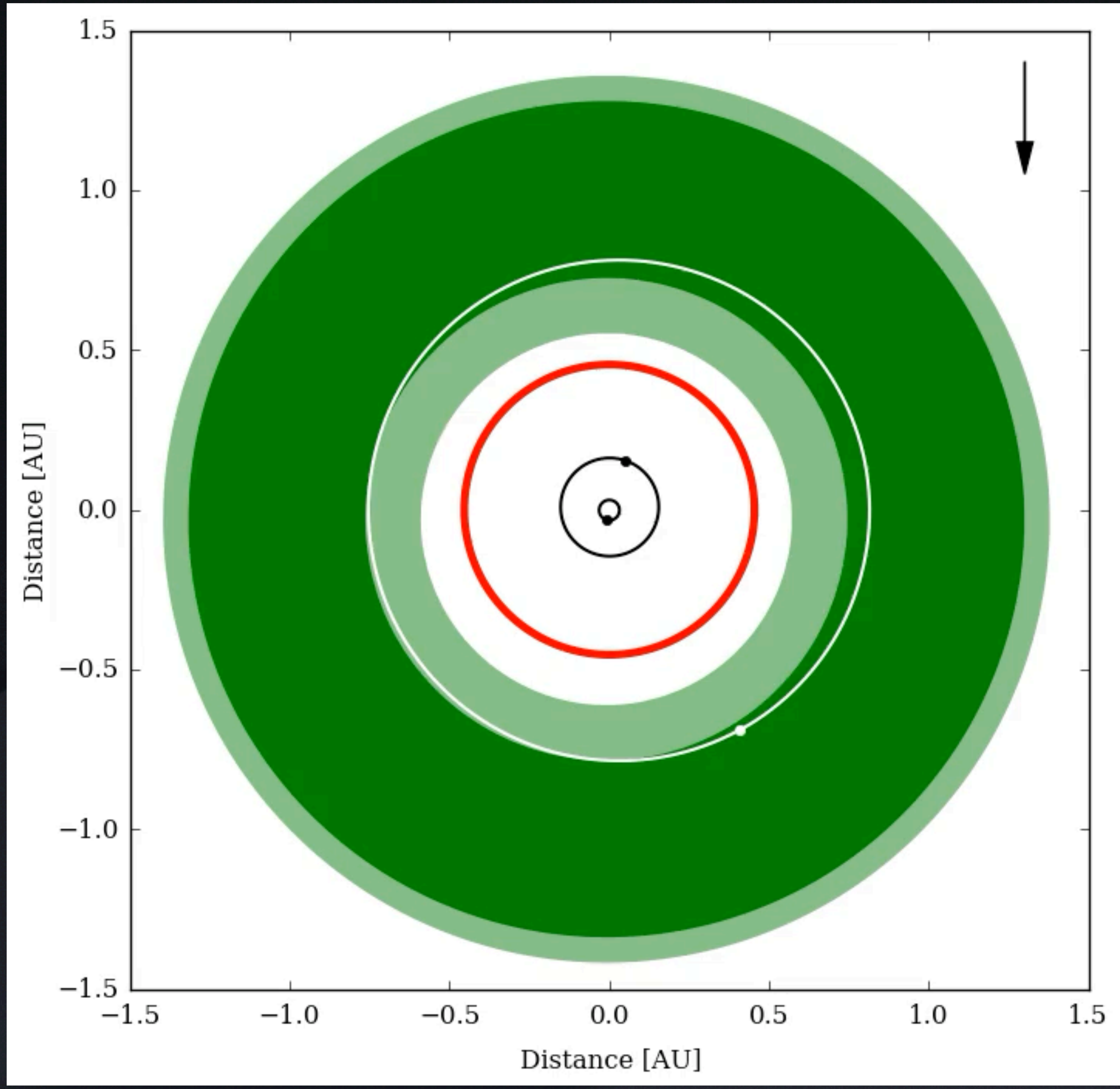
Habitability considerations

Not so different than HZs around single stars!

IMPORTANT CAVEAT: HZs are *dynamic*

Shown: Kepler-453 system (sun-like star + M dwarf)
Kepler-453b orbiting at 0.79 AU

Credit: Tobias Müller (Müller & Haghighipour, 2014)



Other habitability considerations

- ✳ Might be <u>super-habitable</u>: Migration of planets in disk naturally coincides with HZ
- ✳ Photoevaporation of planet atmospheres due to XUV flux
- ✳ Not yet understood:
- ✳ Effects of magnetic fields
- ✳ Secondary outgassing after photoevaporation

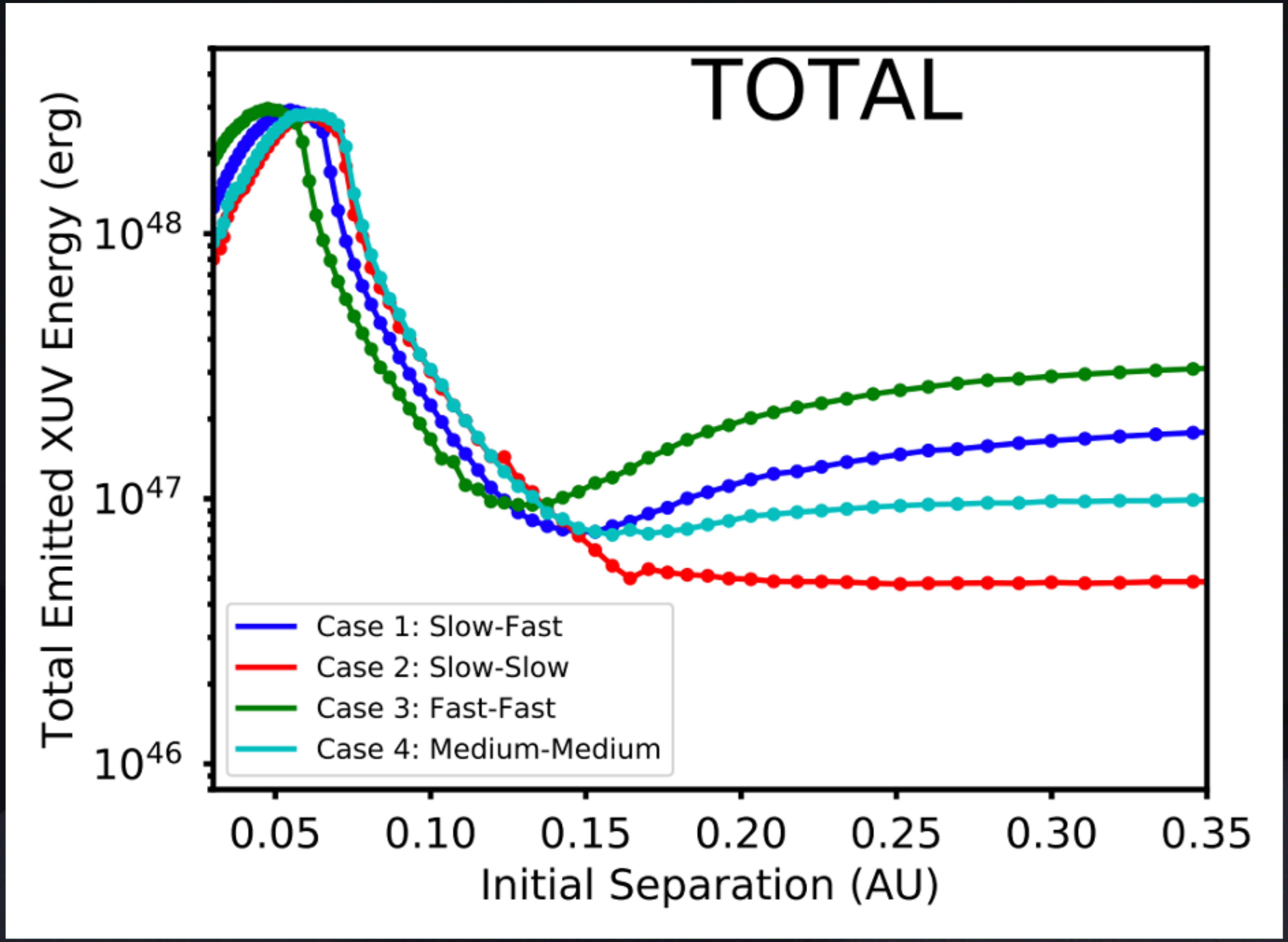
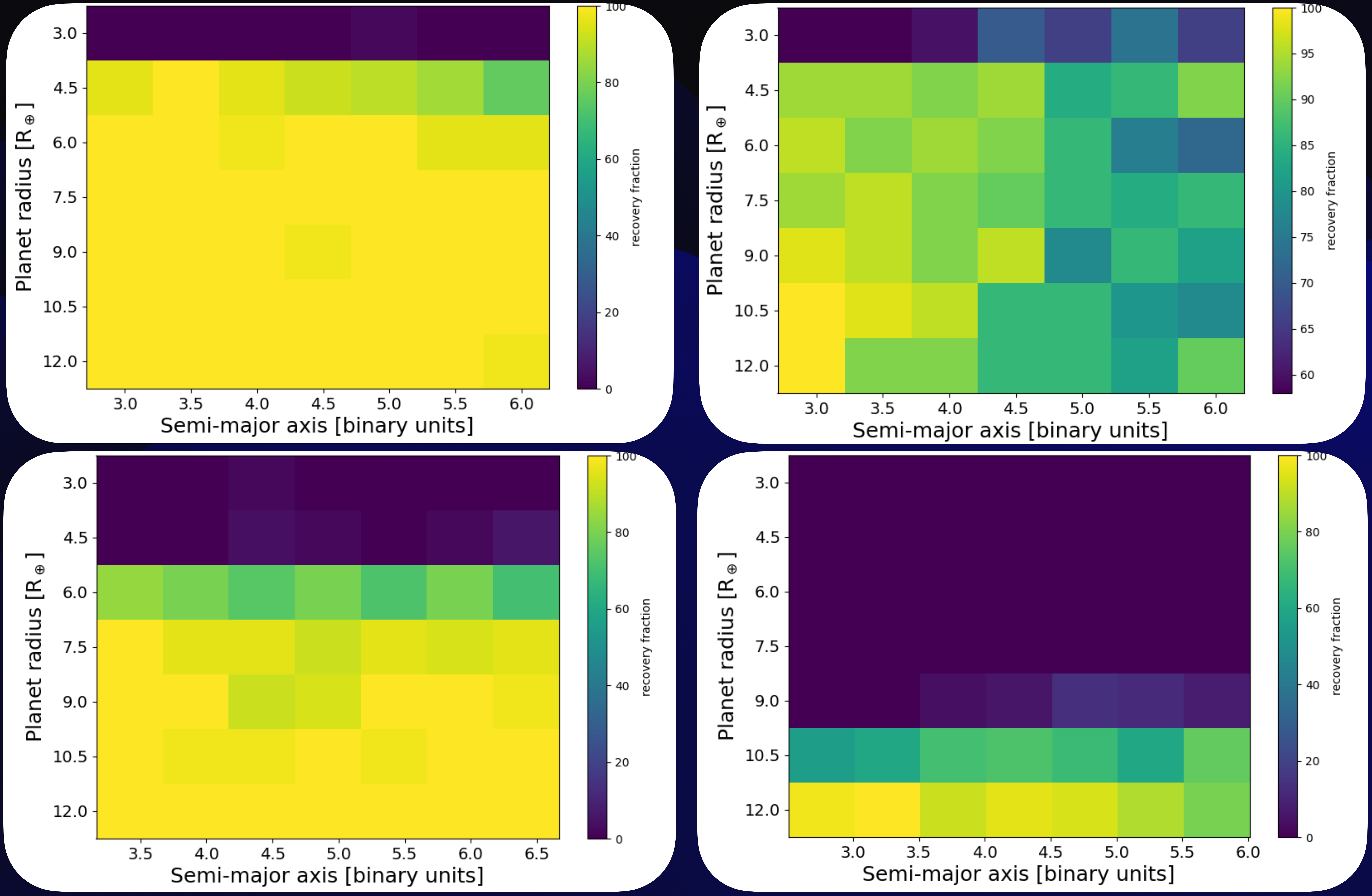


Figure 6 from Johnstone et al., A&A (2019)

Injection Testing

What are we sensitive to in our search? What can we really test?

- Sometimes we have sensitivity to Neptunes or Saturns
- Sometimes we have sensitivity to only giants
- Sometimes there is semi-major axis dependence
- Rarely do we have reliable sensitivity to terrestrial planets



Wrap up

What did we learn?

- ✳Binary stars are interesting!
- ✳Eclipsing binaries in particular give us an exquisite glimpse into stellar properties
- ✳Circumbinary planets (CBPs) tend to be gas giants orbiting solar-type stars with either an M dwarf or another solar-type star
- ✳We're searching for more CBPs in TESS light curves!


Questions?

Future Directions

Work to be done

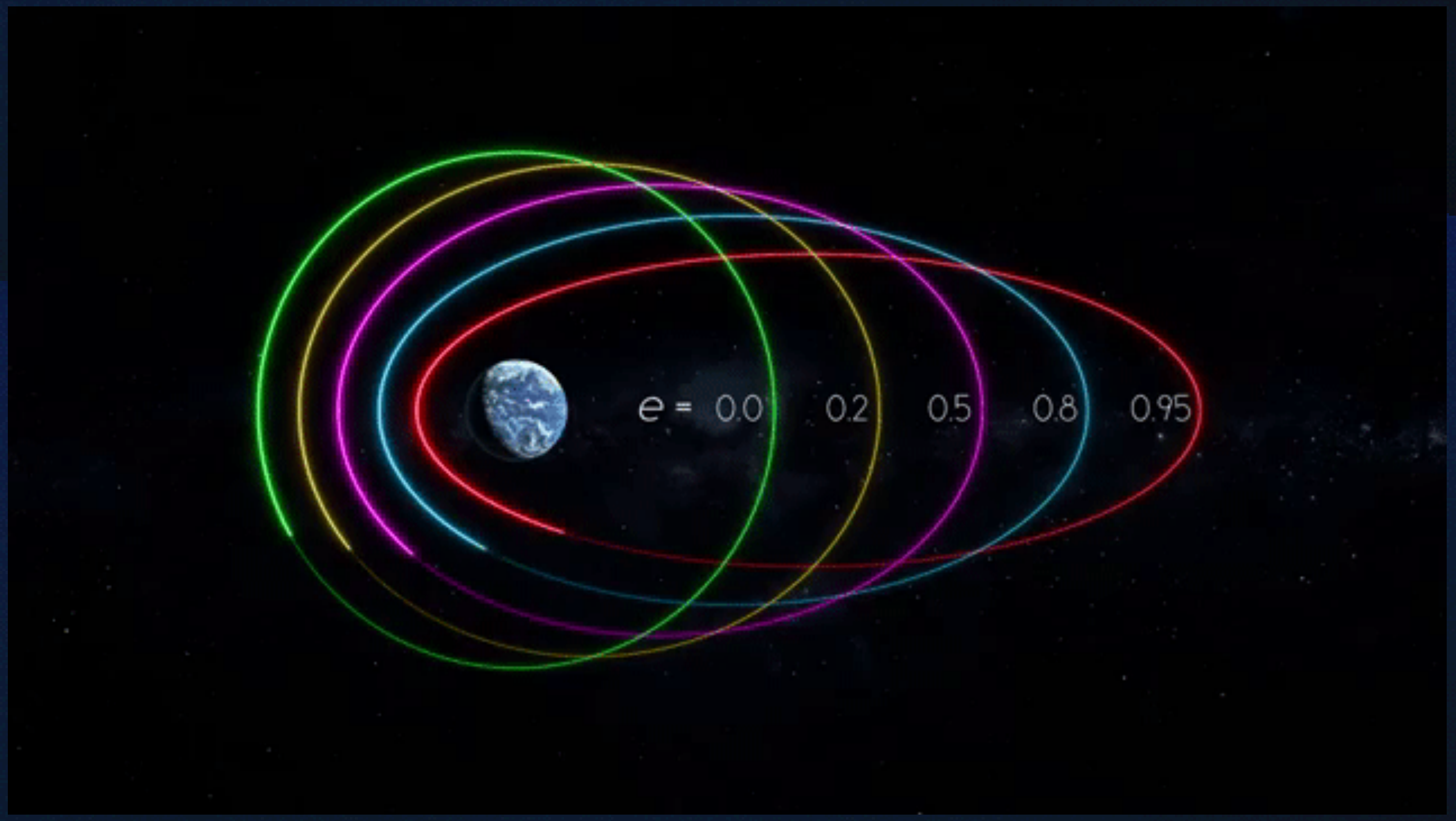
- Finish vetting candidate detections and refit using a more realistic model
- Continue binary modeling
  - Introduce to UNM-CARC
- Injection and recovery
  - Still working through deepening injections; currently at TPF level but doesn't go through whole SPOC light curve generation process (currently SAP)
  - Synthesize populations of planets to detect (rather than individual basis each time)
- Calculate occurrence rates
  - Examine current biases and introduce corrections
- See what we can find in FFI sample (will be 15-20x larger sample!)

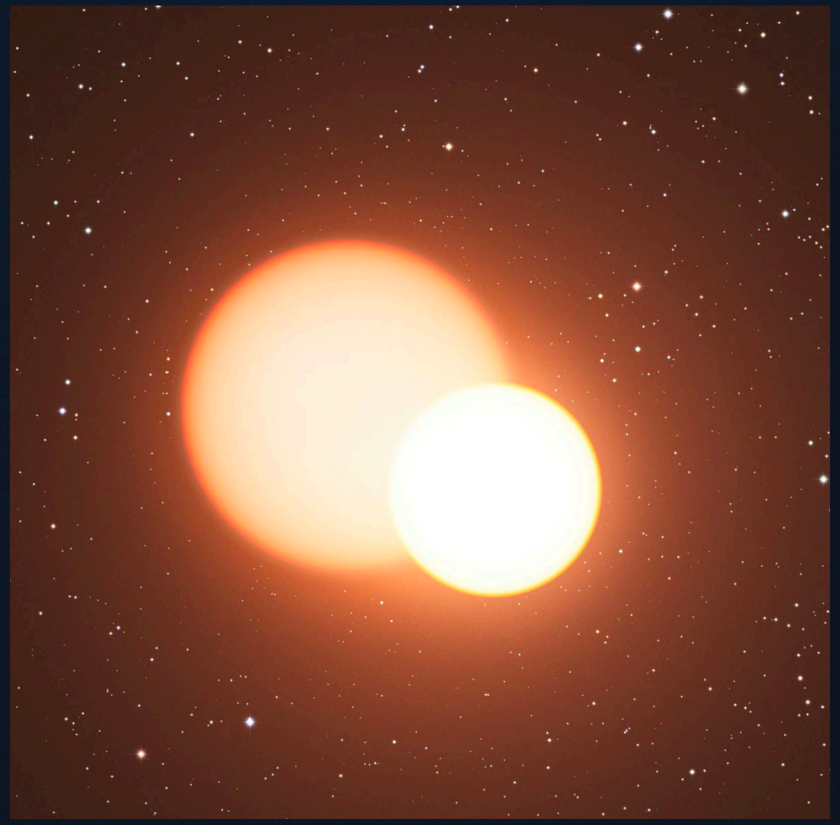
Places We Cannot Go

Stability limit imposed by the binary

$$a_{crit} = a_{bin}[A + Be_{bin} + C\mu_{bin} + D\mu e_{bin} + E\mu_{bin}^2 + Fe_{bin}^2 + Ge_{bin}^2\mu_{bin}^2]$$

Holman, M. J., & Wiegert, P. A. 1999, AJ, 117, 621

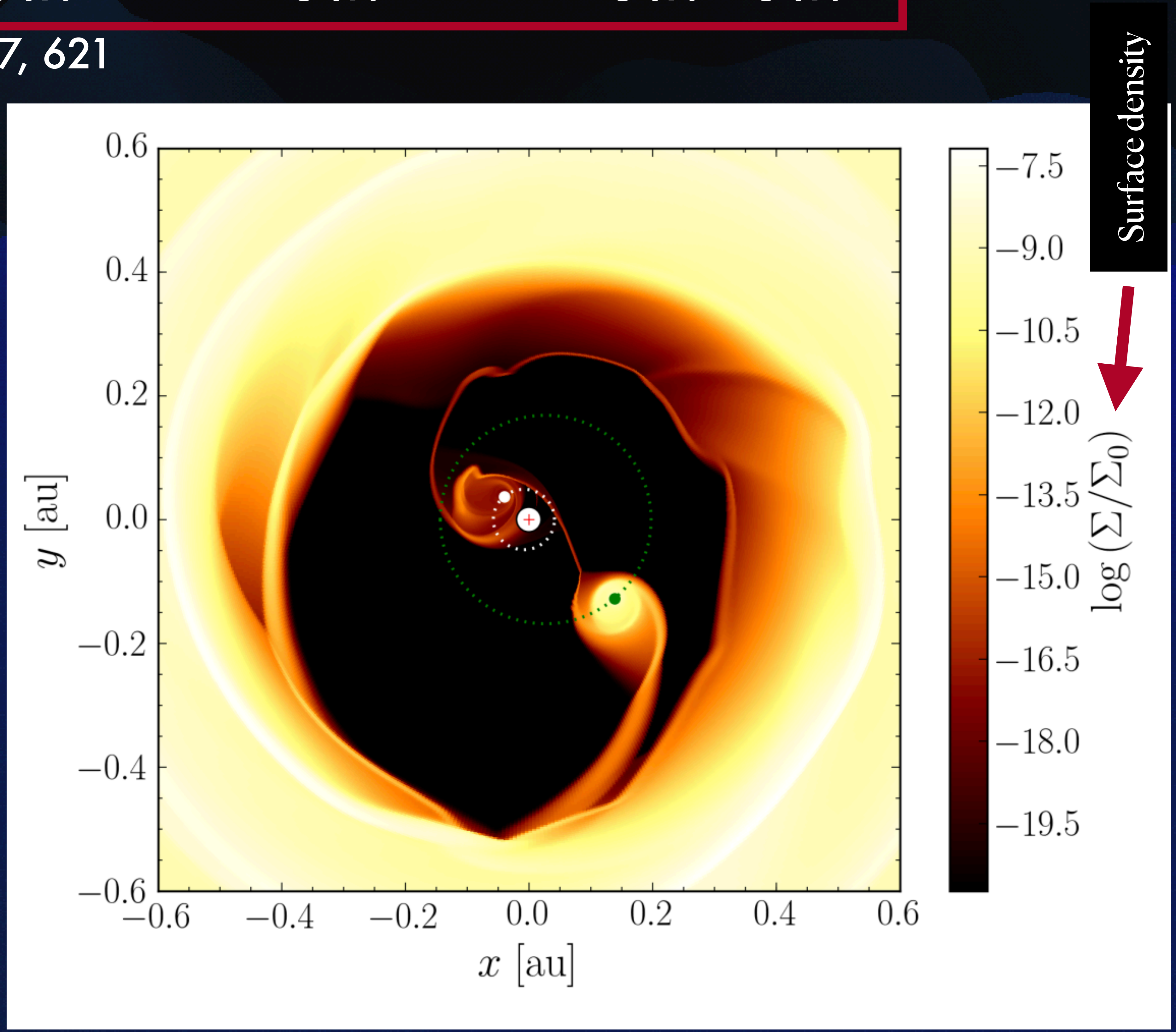




Stability limits depend on:

- a_{bin}: Binary semi-major axis
- e_{bin}: Binary eccentricity
  - Higher e, larger a_{crit}
- μ_{bin}: Binary reduced mass ratio

$$\mu_{bin} = \frac{M_2}{M_1 + M_2}$$

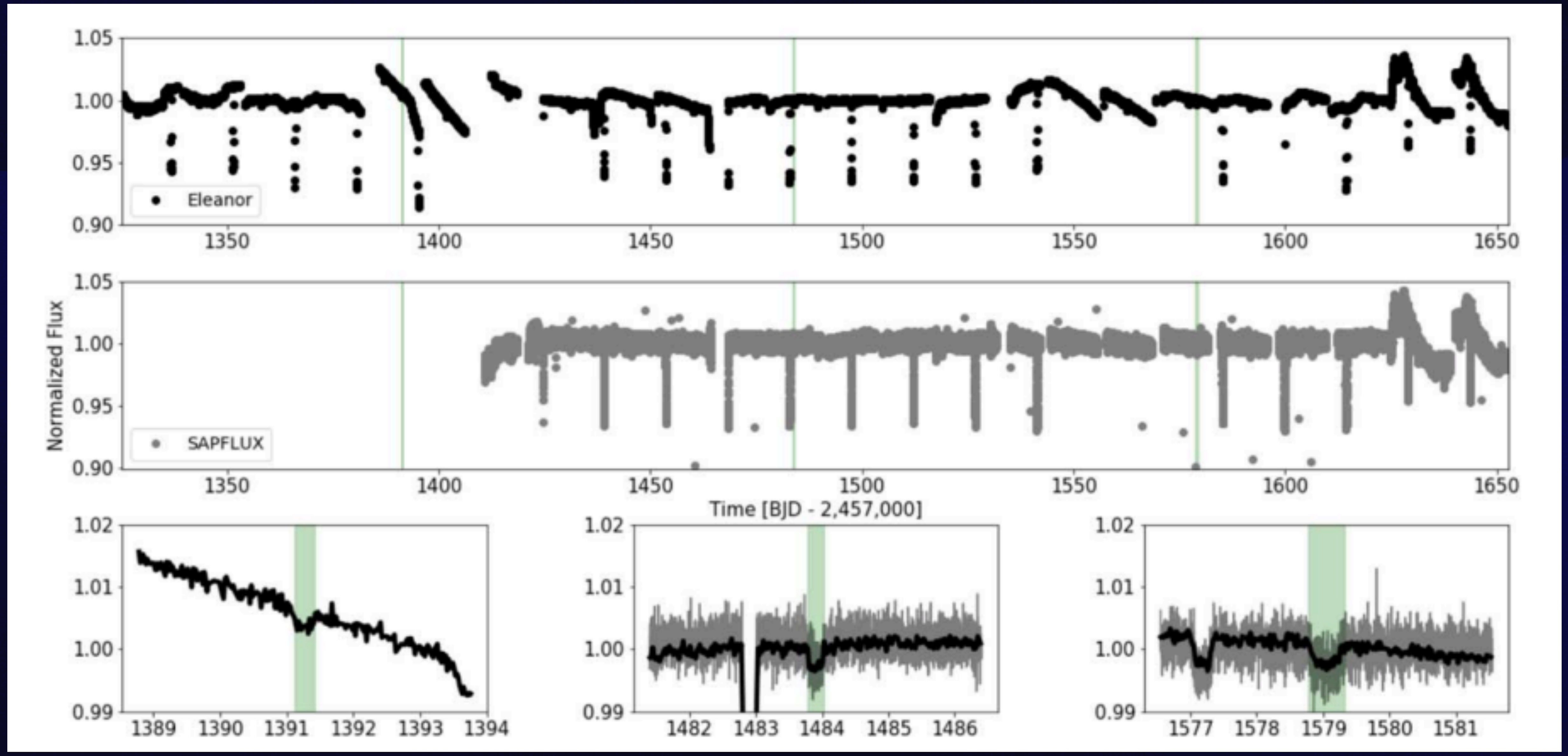


Copied Fig. 1 from Thun, Kley, & Picogna (2017)
Simulation of Kepler-16 system shows absence of material inside a critical orbit!
Primary and secondary orbits shown in white and green, respectively

Detection of new transits of TOI 1338 b

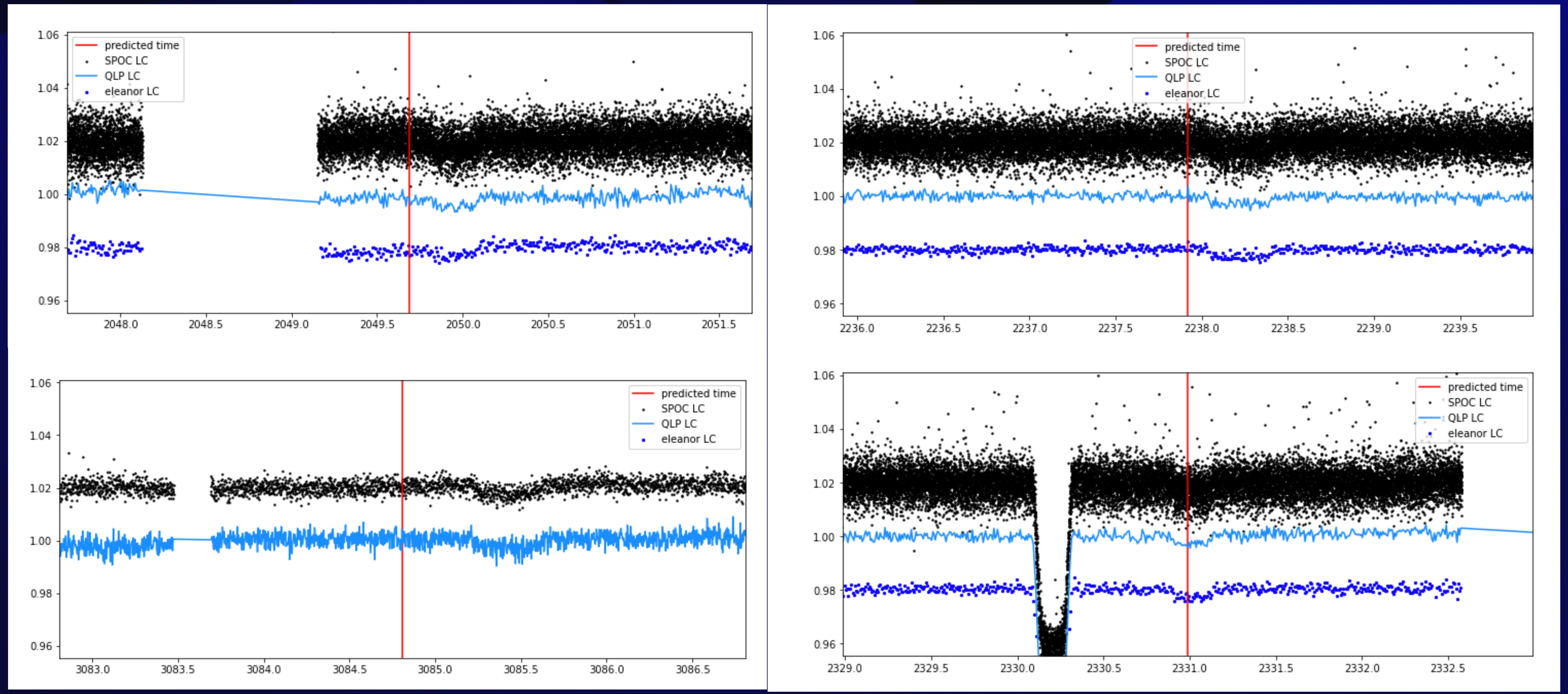
Discovery published in 2020

Saturn-sized planet orbiting a G+M binary



Four new transit events since publishing!

Differences between predicted and actual transit times are indicative of an extra, non-transiting planet in the system (confirmed earlier this year in Standing et al.)



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- IMPORTANT CAVEAT: CBP HZs are *dynamic*

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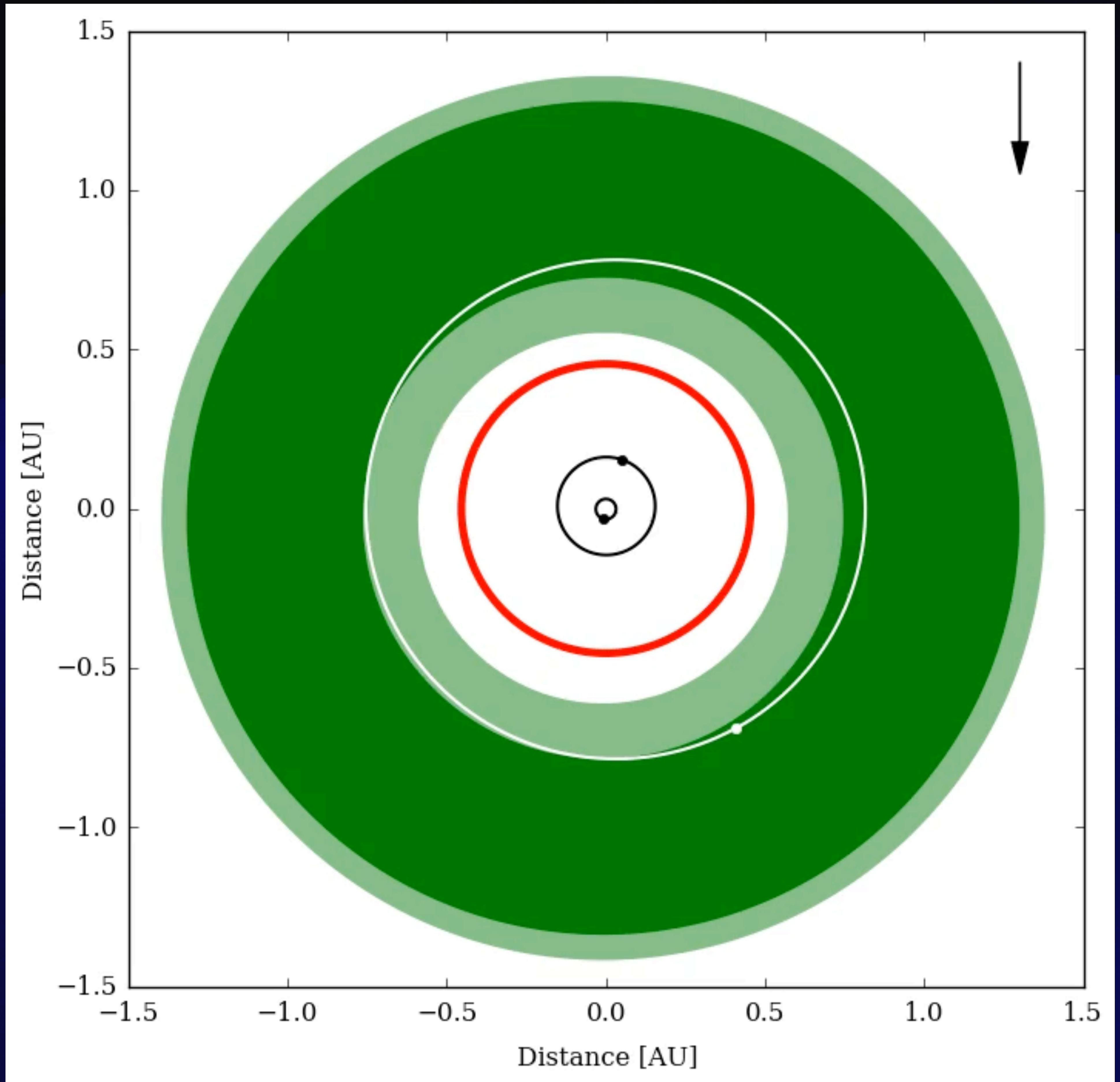
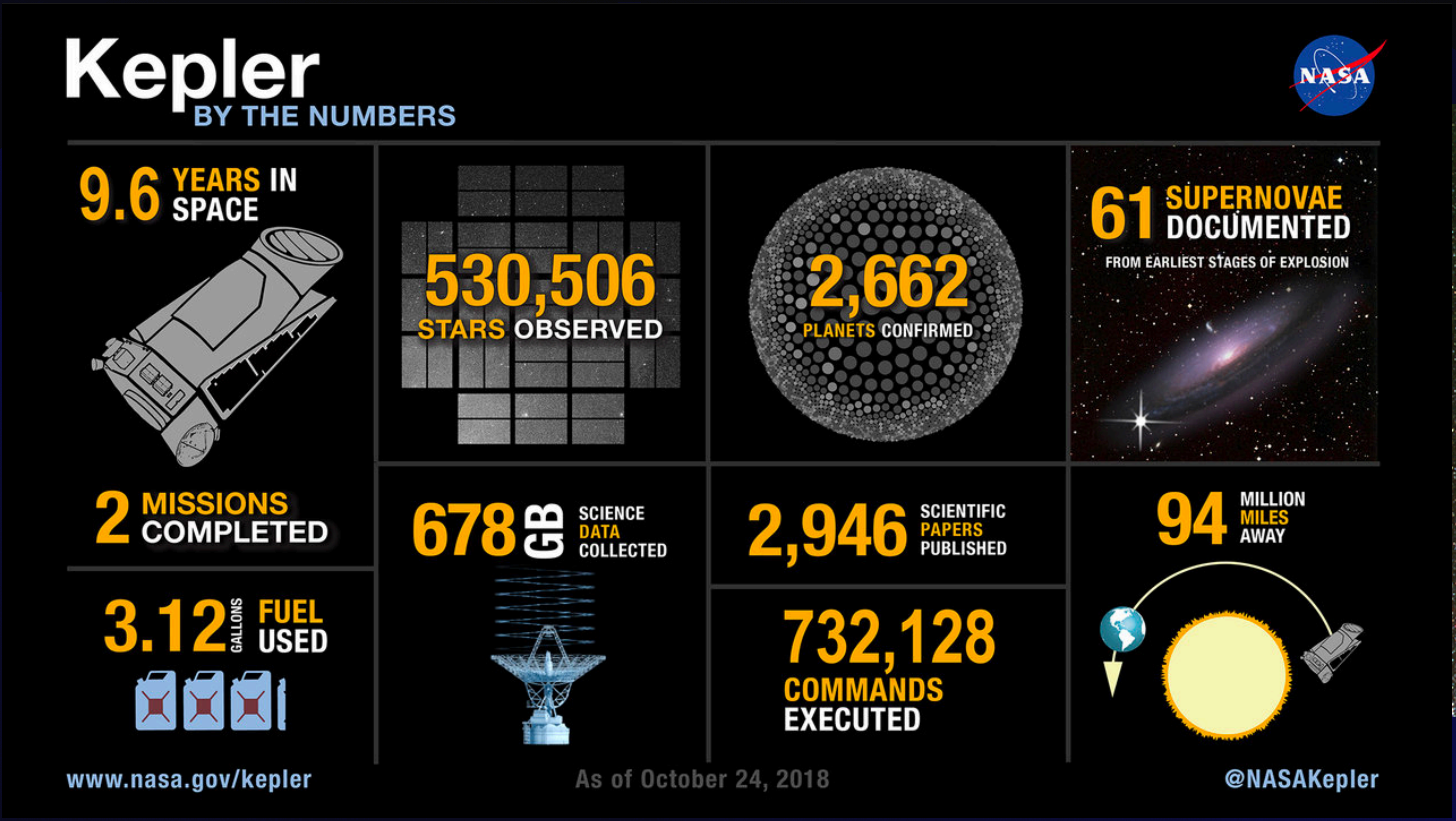
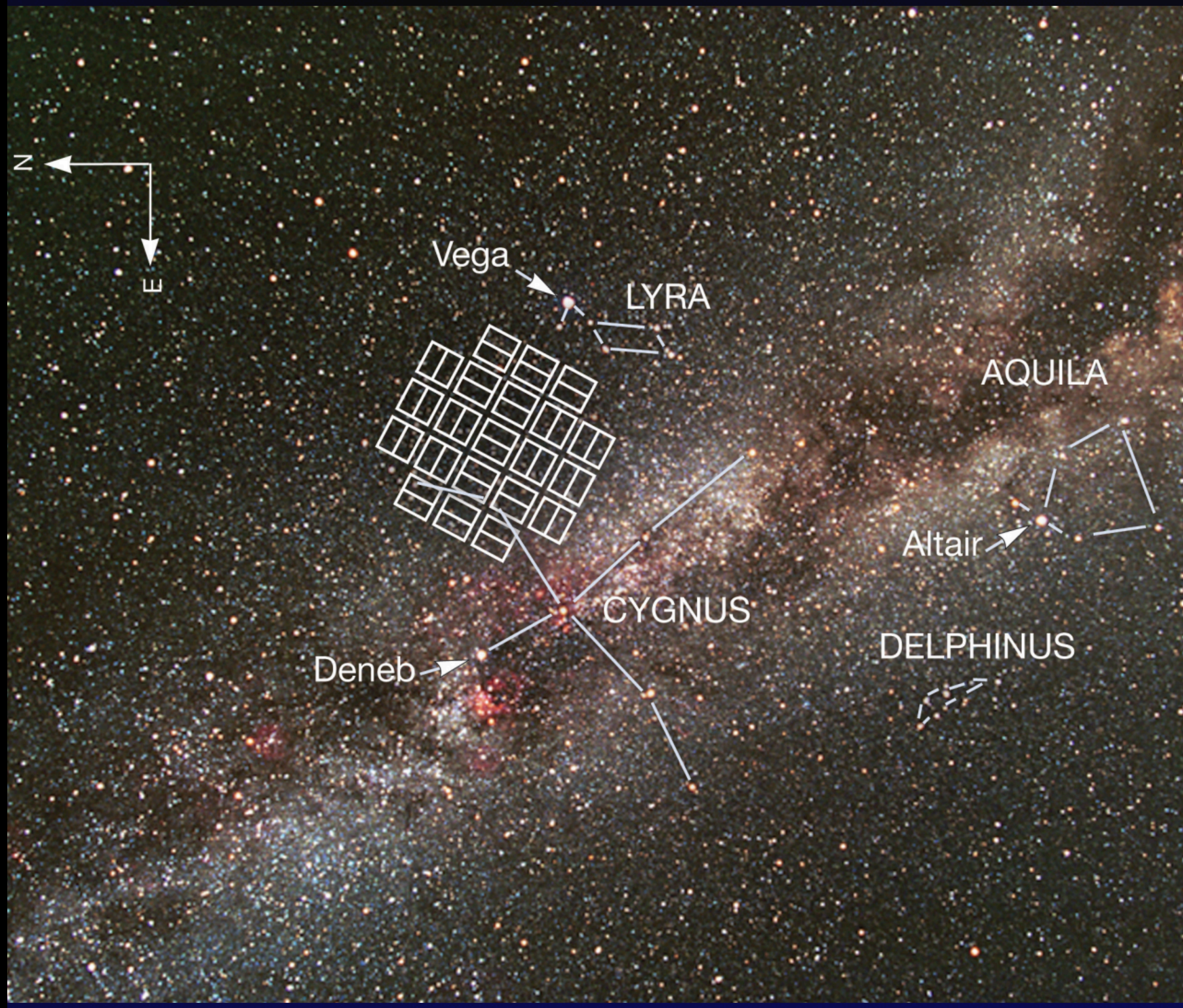


The Kepler Space Telescope





Transits & Eclipses

Our window to the sky

- Allows us to constrain physical sizes and orbital properties of things that we see!
- For binary stars, we have to contest with the fact that both stars are luminous
- Good photometric models of tight binaries will include effects like:
  - Stellar spots
  - Limb darkening
  - Light travel time corrections
  - Doppler boosting
  - Detached-ness